THE ASTROPHYSICAL JOURNAL, Vol. 148, May 1967

A PHOTOELECTRIC RADIAL-VELOCITY SPECTROMETER

R. F. GRIFFIN
The Observatories, Madingley Road, Cambridge, England
Received August 30, 1966

ABSTRACT

This paper discusses the principles of measuring radial velocities directly with a photoelectric spectrometer and describes an experimental instrument for use in such measurements. Possible sources of systematic error are discussed, and reasons are given for supposing them to be capable of producing errors only of the order of 0.1 km/sec. Observations of bright late-type stars confirm the freedom of the method from appreciable systematic errors. They demonstrate that the standard deviation of one photoelectric measurement of the velocity of a 5-mag star is about 1 km/sec, practically the same as that of an *a*-quality velocity in the *General Catalogue of Stellar Radial Velocities*. Using a 36-inch telescope, one can determine velocities of stars at least as faint as $m_v = 9$ at a rate of 6–8 per hour.

I. INTRODUCTION

It is almost a hundred years since the first attempts to measure stellar radial velocities were described by Sir William Huggins (1868), who observed visually the displacement of stellar Balmer lines with respect to the emission lines given by a hydrogen discharge tube. Photography was systematically applied to radial-velocity determinations by Vogel (1892), who used a prism spectrograph giving a reciprocal dispersion of 13 Å/mm. He usually superimposed the Hγ line from a hydrogen lamp upon the stellar spectrogram; a spectrogram of sunlight was used as a standard, the star's velocity being derived from the relative displacement between the Hγ emission lines when the stellar and solar spectra were brought into register alongside one another. Vogel, however, sometimes used an iron arc as the reference source. Notable contributions to the development of spectrographs free from serious flexure and thermal instability were made at the Lick Observatory by Campbell (1898) and Wright (1907), and the technique of photographic radial-velocity determination they were perfecting at the turn of the century has been in use ever since. Later improvements in the sensitivity of photographic emulsions and the development of blazed gratings and Schmidt cameras have, however, allowed some increase in accuracy and considerable gain in speed of observation during the last 60 years.

Elementary considerations show that photography of stellar spectra is a fundamentally inefficient method of measuring radial velocities: although the aim is to deduce a single quantity—the Doppler shift—the method involves recording separately many hundreds, often thousands, of independent elements of the spectrum. Furthermore, it uses as a detector the photographic emulsion, which is well known to have a very low quantum efficiency. There is evidently considerable scope for the development of instruments in which some of the shortcomings of the conventional method are avoided, specifically for measuring stellar Doppler shifts.

II. THE PRINCIPLE OF THE RADIAL-VELOCITY SPECTROMETER

The purpose of this paper is to describe an instrument with which stellar radial velocities may be measured directly as linear shifts in the spectrum. This instrument uses a matching technique: the stellar spectrum is brought into register with an appropriate diaphragm (upon which it is focused) by scanning the diaphragm along the direction of dispersion with a micrometer screw, and the match is monitored photoelectrically. The idea of matching superimposed spectra is not new; Evershed (1913) used the method for measuring solar spectrograms at Kodaikanal, and it forms the basis of spectral comparators in use at several observatories. Its direct application to stellar spectra has been suggested by a number of authors (particularly Babcock 1955 and Fellgett 1953). The Hartmann (1904) spectrocomparator, although using a technique of optical superposition, was intended for matching adjacent, not superposed, spectra, and is to be regarded as a refinement of Vogel's method rather than a forerunner of Evershed's.

The principle of the instrument described here, which may be termed a radial-velocity spectrometer, involves the use in the focal surface of a spectroscope of a diaphragm which, instead of having a few discrete apertures as is the case in the narrow-band photometry developed at Cambridge several years ago (Griffin and Redman 1960; Griffin 1961), has a transmission which varies along its length in a manner related to the spectrum typical of the stars to be observed. An obvious example of such a diaphragm is a spectrogram.

Suppose a widened spectrogram is obtained, through the optics of the spectrometer, of, say, a bright K star; and that it is returned after processing to the focal surface where it was exposed, the telescope too being turned to the same star. If the spectrogram is replaced accurately in register with the stellar spectrum, all the bright parts of the spectrum will be systematically obstructed by heavily exposed emulsion, and rather little light will pass through the spectrogram. If it is not in register, the obstruction of the spectrum will not be systematic and the total transmission will be greater.

It is therefore to be expected that, if the spectrogram (or diaphragm as I shall now call it) is scanned through the position of register, a minimum of light will be transmitted at that position. The light which passes the diaphragm can be measured by a photomultiplier after imaging by a Fabry lens, and the effects of seeing, etc., can be largely annulled by simultaneous measurement of the light in comparison bands in the usual way (Griffin and Redman 1960).

The telescope may then be directed to another star whose spectral type is not too different from that of the first, and the diaphragm may be brought into register with the new spectrum. The direction and distance through which the diaphragm has to be moved are direct measures of the difference in radial velocity between the two stars.

At the present stage of development of the technique, the absolute values of radial velocities are not determined, only the relative values for different stars. In practice, a reference star is observed from time to time, and the velocities of all other stars are referred to it. To obtain the absolute velocities it is necessary to know that of the reference star(s).

This method appears to offer the possibility of substantially higher sensitivity than that obtainable by the conventional photographic technique since, instead of a dispersed spectrum being observed, the light from the whole of the spectral region used for observation is received upon a single photomultiplier cell, itself a much more sensitive detector than the photographic emulsion. However, the advantage is partly offset by the presence of the diaphragm, which in most cases will need to have a transmission only of the order of 10 per cent or less for good discrimination of the position of register; and by the necessity of scanning it along the spectrum, which amounts to making a number of consecutive, independent observations.

A second aspect of the photoelectric radial-velocity technique in which it may in principle be expected to be superior to photography is that the same high spectral resolution can be used in observing faint stars as bright ones. Therefore, although lower signal-to-noise ratios will result in larger errors for fainter stars, the accuracy of radial-velocity measurement for faint stars may well be higher than that obtainable photographically with the drastically curtailed resolution dictated by the practical limits to exposure times.

Another way of looking at the fundamental difference between the two methods is as follows. If the Doppler displacement of the spectrum has to be derived from the positions of its individual features, it is necessary to record the spectrum in dispersed form. To record the individual elements of the spectrum simultaneously—and unless the total number of elements is very small, it is hopelessly inefficient to do otherwise—requires the use of a multichannel detector: conventionally the photographic emulsion, although other detectors are now becoming practicable and are worth consideration. The accuracy with which the Doppler displacement can be measured from a record of the dispersed spectrum may be held to depend upon the number of features available for measurement and upon the resolving power exhibited by the record; it will therefore increase with the number of spectral elements independently recorded. Since the light energy required to produce an acceptable record of one element of the spectrum on the photographic emulsion (or other multichannel detector) is a constant, it follows that the fainter the star being observed, the smaller is the number of elements of its spectrum which can be recorded in a given exposure time and the lower the accuracy of determination of the Doppler displacement. By contrast, the new technique involves only the measurement of the total radiation passed by a given optical apparatus and therefore calls only for a single-channel detector, the photomultiplier cell, which happens also to have a much higher quantum efficiency than the traditional multichannel receiver. Furthermore, the highest possible resolution can always be used, independently of the brightness of the star observed; no matter how faint the light may be in the focal surface of the spectrum where the spectral displacement is determined, it is just as readily collected by the Fabry lens and transmitted to the photomultiplier. Thus a fraction—equal to the fractional transmission of the diaphragm—of the number of spectral elements resolved where they are focused on the diaphragm (the number which determines the accuracy of measurement) is imaged on the photomultiplier cathode as, in effect, one single element (the number which determines the rapidity of measurement). It is evident that the ratio of these two numbers is a substantial "brightness amplification factor" between the light intensities in the spectrum and at the photomultiplier, respectively, and represents an equally substantial advantage of sensitivity in favor of the new technique.

III. AN EXPERIMENTAL RADIAL-VELOCITY SPECTROMETER

a) Spectrometer Optics

A radial-velocity spectrometer working on the principles outlined above has been constructed at the Cambridge Observatories. It is an experimental instrument, a modification of one originally designed for an entirely different purpose (Griffin 1961), and in many ways is far from suitable for the present application. A diagrammatic section through the spectrometer and the 36-inch coudé reflector with which it is used, showing the optical layout, is given in Figure 1. The spectrometer has a 6-inch collimator and uses a Bausch and Lomb 600 line/mm replica grating in the second-order blue; a doublet camera lens of 103 inches' focal length gives a reciprocal dispersion of 3.17 Å/mm.

An entrance slit 1″ wide projected on the sky—as wide as was judged permissible to use without courting serious guiding errors—is used for radial-velocity observations. The intrinsic resolving power of the spectrometer is so high that the instrumental profile is largely determined by the width of the entrance slit. It approximates to a rectangular profile 64 μ wide, corresponding to 0.20 Å, or 13 km/sec, in the spectrum.

The coudé image reflected from the polished jaws of the entrance slit is re-imaged at an eyepiece at the observer's desk, which is situated at the northwest edge of the upper floor of the dome; control panels for the telescope and electronics, and the strip-chart recorder which draws the results of radial-velocity observations in the manner described in § III*e* below are also grouped there.

b) *The Diaphragm*

The diaphragm extends between limiting wavelengths of λ4369 and λ4827 Å, and was constructed with reference to the spectrum of Arcturus (spectral type K2 III). After a thorough investigation had been made by numerical integration of the properties of diaphragms of positive and negative, low and high contrasts for a sample region of the spectrum (λλ4500–4560 Å), infinite negative contrast was chosen; that is to say, the diaphragm transmits all absorption lines, of whatever origin, wherever their residual intensities as observed in the spectrum of Arcturus at the focus of this spectrometer are

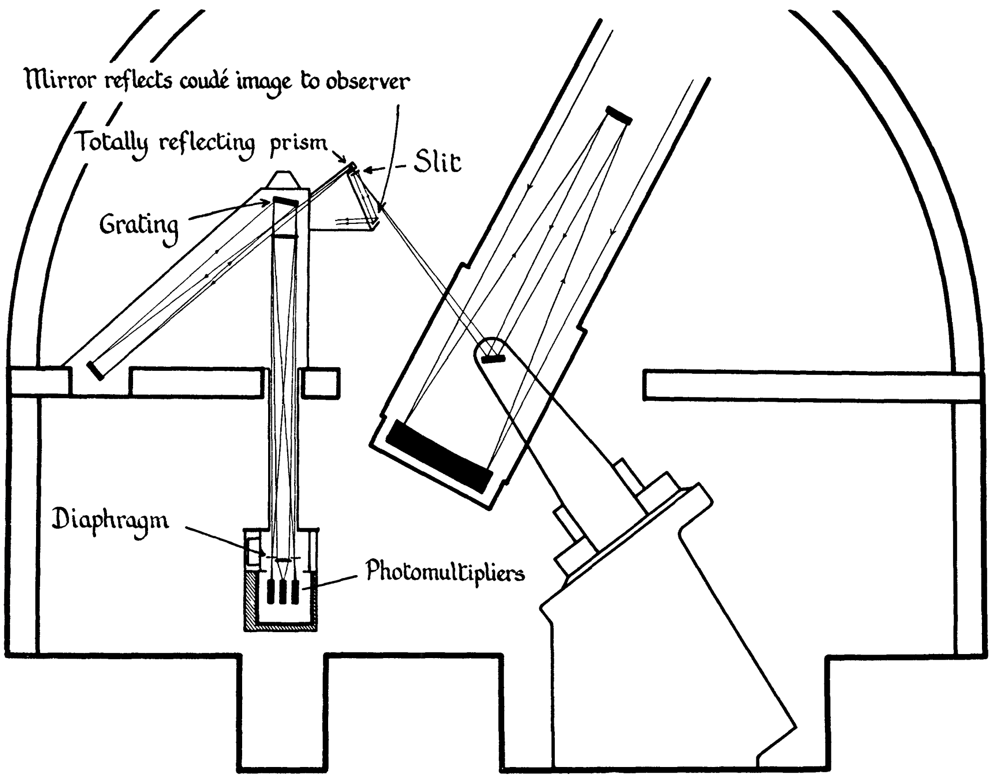

FIG. 1.—Sectional diagram of the Cambridge 36-inch coudé reflector and radial-velocity spectrometer

less than a critical value, and is completely opaque elsewhere. The apertures which would have transmitted the very strong and wide iron lines at λ4383, λ4404, and λ4415 Å were, however, arbitrarily suppressed.

The diaphragm was constructed by scanning a fine-grain, high-contrast photographic emulsion slowly and continuously past the image of a long narrow slit which was illuminated by a lamp. This lamp was switched off whenever it was desired to create an aperture in the developed diaphragm. The advance of the carriage carrying the future diaphragm was monitored by a moiré fringe system; the fringe counter was placed in another room, where also the writer sat and for 8 hours switched the lamp on and off in accordance with a predetermined schedule. A spectrogram of Arcturus exposed through the spectrometer and digitally recorded at 8-μ intervals formed the basis of the schedule. This primitive scheme worked so well that quite respectable gratings having 50 line pairs per millimeter were made by it in preliminary trials, and it permitted the construction of a diaphragm conforming very closely indeed to the desired characteristics.

Owing to the digital nature of the construction procedure, the widths of all the apertures in the diaphragm are in multiples of 8 μ. There are 234 apertures, ranging from 8 to 232 μ in width with a mean of 70 μ; their widths are distributed in accordance with Table 1. The total transmission of the diaphragm is 11.3 per cent of the spectrum between the limiting wavelengths given above.

c) *Fabry Optics and Photomultipliers*

The light transmitted by the apertures in the diaphragm is all collected by a 6-inch f/1 aspheric Fabry lens which images the illuminated ellipse on the diffraction grating onto the photocathode of an EMI type 9558 photomultiplier. No suitable lens was immediately available commercially, so one was made by the writer out of Perspex (Lucite) by turning on a lathe. Comparison bands at wavelengths of approximately $\lambda\lambda$4250–4350 and $\lambda\lambda$4850–4900 Å are received on other cells.

Since the spectrometer was first described (Griffin 1961) the camera end has been completely redesigned with a view to measuring radial velocities and the arrangements for cooling the photomultipliers have been changed. The photocells are now housed in a box made of thick Perspex; the top of the box consists of a very thick Perspex screen, which serves to prevent the cold beneath from spreading to the rest of the spectrometer. The large Fabry lens is incorporated in the screen, in which also there are small apertures for the light in the comparison bands to pass through. The Perspex box allows its contents to be inspected when cold without exposing them to the outside air and causing frosting; it is maintained at a temperature of $-20°$ C by circulating the air in it through an external heat exchanger coupled to a domestic refrigerator unit. Stray light and Earth's magnetic field are excluded from the box by an outer μ-metal shield, which can be lowered into a hole in the floor when access to the equipment inside is required.

TABLE 1

DISTRIBUTION OF WIDTHS OF APERTURES IN RADIAL-VELOCITY DIAPHRAGM

Width (units)*	1–5	6–10	11–15	16–20	21–25	26–29	All
Number of apertures	72	92	42	21	5	2	234

* Unit of width = 8 μ = 1 61 km/sec

d) *Electronics*

Pulse-counting electronics (Yates 1948) are employed in association with rate meters which allow the results to be displayed on a strip-chart recorder. Pulse preamplifiers using transistors are built directly onto the photomultiplier bases; the end of each multiplier, with its base and preamplifier, is encapsulated in silicone rubber. This treatment, together with maintenance of the cathodes at earth potential, effectively renders the electronics immune to interference through dampness, formerly a serious difficulty in the Cambridge climate. After further amplification outside the cold box, the pulses pass to discriminators which reject those (largely unwanted noise) of less than a certain height and tailor the acceptable ones to a standard height and character. In this way all the accepted pulses are given equal weight instead of being weighted in proportion to their (very varying) sizes.

The output pulses from the discriminator of the central channel (the one receiving light from the radial-velocity diaphragm) go to a rate meter which gives a current proportional to the rate of arrival of pulses; this current is recorded by a Brown recorder. The comparison channels, whose relative sensitivities are adjusted to equality for stars of color similar to that of Arcturus, feed a second rate meter. Its output is used to provide the reference voltage on the Brown recorder slide wire in place of the usual fixed reference voltage; the recorder therefore shows the ratio between the central channel and the sum of the comparison bands. It is appreciated that the use of rate meters involves some loss of efficiency, but this has so far been considered worthwhile in view of the immediate intelligibility and simplicity of reduction of the resulting traces.

All the electronics used in this research were designed and constructed by Mr. D. W. Beggs at the Cambridge Observatories. They have worked well and reliably in the variable and adverse conditions of temperature and humidity obtaining in the dome.

e) Observing Technique

The radial-velocity diaphragm is scanned along the spectrum by a micrometer screw geared from a magslip (Selsyn). Various speeds are available, but the one which has proved by far the most useful is about 80 km sec min^{-1}. One observation consists of scanning the diaphragm continuously toward the violet at this constant rate from a position corresponding to a large positive velocity until the Brown recorder has drawn the minimum diagnostic of the star's radial velocity, and then scanning back again. The observer does not, therefore, attempt to determine the position at which the diaphragm is in register with the stellar spectrum at the time of observation, but deduces it afterward from the position of the minimum in the transmitted light recorded on the chart. For convenience, this minimum in the function drawn by the Brown recorder (the cross-correlation function of the stellar spectrum with the diaphragm) will be referred to as "the dip" in what follows.

Owing to the electronic time constants built into the rate meters (and also, no doubt, in part to mechanical backlash at several points), the forward and reverse scans give results which have a constant difference from one another. Since a single observation consists of a forward and a reverse scan, and the mean is taken as the result of the observation, no error or inconvenience arises on this account.

In order to measure the positions of the dips on the Brown recorder trace, microswitches associated with the micrometer gearing system short-circuit the signal momentarily at intervals of about $12\frac{1}{2}$ km/sec, causing sharp downward "spikes" on the trace. Other microswitches short-circuit the reference signal one-quarter as often; they provide upward spikes after every fourth downward one. The upward spikes are asymmetrically placed with respect to the downward ones, and make it possible to distinguish between forward and reverse scans as well as facilitating counting of the spikes. All radial-velocity measurements are made simply by bisecting the dips on the trace with a line ruled on a piece of Perspex, and estimating their positions with reference to the "fiducial fence" of downward spikes. A diagrammatic trace and a real one are shown in Figure 2.

IV. SOURCES OF ERROR

There are several instrumental difficulties which may be considered to affect the radial-velocity spectrometer. Some of them are general to this technique, but some are specific to the experimental instrument, which as I have said was designed for another purpose and is far from ideal. In particular, the present equipment is not stable against temperature changes and is in a very exposed position in the dome; it shows rapid and irregular changes of the instrumental velocity zero, which necessitate much time being spent in observing reference stars. Furthermore, the same basic spectrometer is used for routine narrow-band spectrophotometry as for radial-velocity measurements. At the beginning of each radial-velocity observing run, reassembly of the equipment and the necessary somewhat delicate adjustments occupy most of a day; until an instrument can be reserved solely for radial-velocity determinations for long periods the technique cannot be regarded as routine in the sense of being available for use at short notice by operators unacquainted with the details of the equipment.

Perhaps the most serious difficulty is the effect of a disparity in scale, or "mismatch," between the stellar spectrum and the diaphragm. The spectrometer is so designed that the scales can always be adjusted to agree for zero radial velocity, the adjustment being monitored by visual observation of iron arc lines through the many apertures in the diaphragm which correspond to unblended iron lines in the star. Mismatch is, however, bound to occur when stars of finite radial velocity are observed because the Doppler shift is proportional to wavelength and the reciprocal dispersion of the instrument is not. However, even with the rather broad wavelength band and high resolution which I have employed, the dips exhibited on the Brown recorder chart are not appreciably degraded at the highest velocities (~100 km/sec) yet observed. Since the band width is one-tenth of the mean wavelength, the Doppler shift will differ by 10 per cent between the two

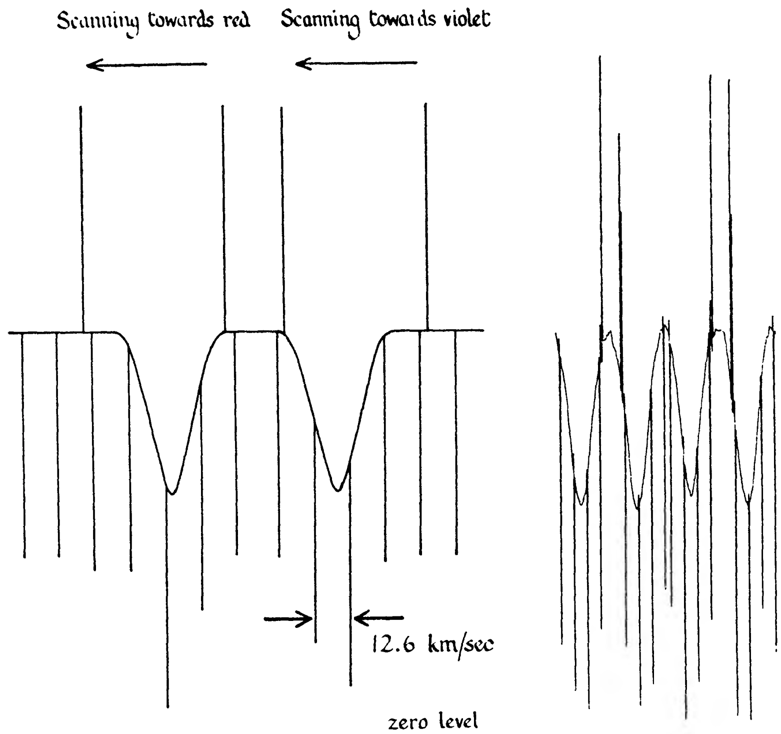

FIG. 2.—*Left:* diagrammatic representation of a radial-velocity observation. *Right:* actual record of an observation of 41 Comae.

ends of the band; therefore a star of velocity 100 km/sec, correctly matched in the middle of the diaphragm, must be mismatched by 5 km/sec at each end. This is the extreme value, and is still only one quarter of the half-width of the dip, which numerical integration and actual observation agree in placing at about 20 km/sec, so it is not surprising that no degradation of the dip has been observed. It is clearly not possible for the position of the dip to be significantly shifted by mismatch without degradation, and no serious error can be introduced by this difficulty at radial velocities less than 100 km/sec. Detailed numerical integrations are planned to investigate how small the effect is.

A somewhat less obvious source of error arises through the combined effects of variations of stellar colors and mismatch. The differences in the energy distributions within the observed wavelength region between stars of the spectral type of Arcturus and, on the one hand, early M giant stars, and, on the other hand, G5 dwarfs, have been found by approximate integrations to give effective wavelengths (observed through the radial-velocity diaphragm) differing by about ± 15 Å, or 0.3 per cent of the effective waveassumption made in the last paragraph this implies that the accuracies of the photoelectric means are all the same, despite the differing numbers of observations upon which they are based. The error involved in this last assumption is not large, as it will be shown that the major part of the discrepancies between the photoelectric and *RVC* velocities is due to the *RVC*.

The zero point of my velocities is arbitrarily adjusted to give agreement in the mean with the *RVC* values. The standard deviation of this transfer of the zero point is 0.20 km/sec. The instrumental zero is followed by repeated observations of reference stars

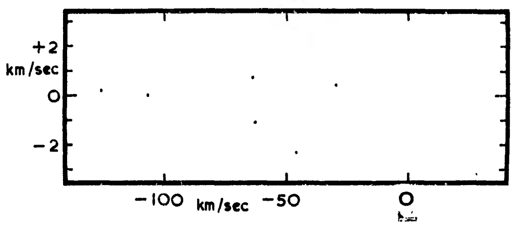

FIG 3

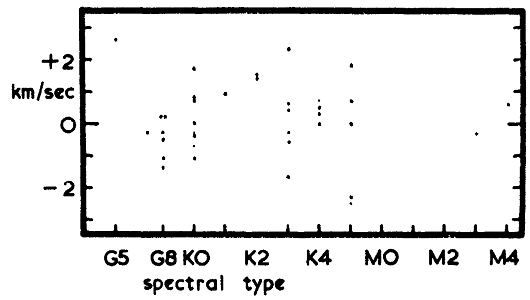

FIG 4

FIG. 3.—Residuals of photoelectric velocities plotted against observed velocity. The abscissae are the approximate geocentric velocities (which of course changed somewhat during the period covered by the observations) relative to that of the primary reference star 41 Com, and therefore are not the same as the heliocentric velocities given in Table 2. Small dots distinguish residuals derived from *RVC b* velocities.

FIG. 4.—Residuals of photoelectric velocities plotted against spectral type. Small dots distinguish residuals derived from *RVC b* velocities.

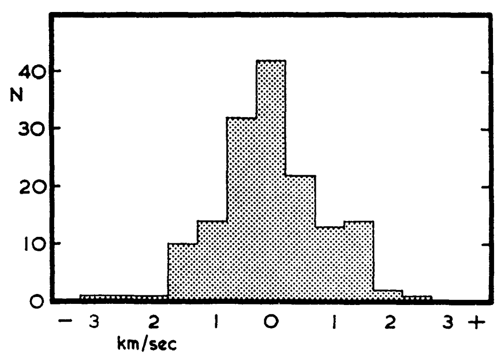

FIG. 5.—Deviations of individual photoelectric velocities from their respective means

(primarily 41 Com and secondarily λ Lyr), but no particular quality is attached to these stars except that the constancy of their velocities is assumed. The velocities derived for the reference stars are −14.6 and −17.2 km/sec, respectively; the *RVC* gives −16.4 and −15.5 km/sec.

Figures 3 and 4 show the residuals given in the last column of Table 2 plotted against two of the quantities which might be held most likely to influence them, observed velocity and spectral type. No systematic trend can be discerned in either graph.

If the deviations of individual photoelectric observations from their respective photoelectric means are averaged night by night, the five "night errors" so derived from the material in Table 2 all prove to be less than their standard deviations; the largest is 0.10 km/sec.

Since, therefore, no systematic component can be detected in the photoelectric errors, it is competent to treat them as random errors. The further assumption will now be made that they represent a normal distribution, that is, each observation is equally liable to error. The deviations of the 153 individual observations in Table 2 from their respective means are shown in Figure 5; the rms deviation is 0.90 km/sec, and taking account of the reduction of the number of degrees of freedom from 153 to 110 through the derivation of the 43 means from the same observations we find:

$$\text{Standard deviation of one photoelectric observation} = 1.06 \pm 0.07 \text{ km/sec.}$$

It is now possible to subtract the contribution of the photoelectric errors from the discrepancies shown in the last column of Table 2 in order to derive the errors of the *RVC*. The standard error of an *a*-quality velocity is found in this way to be 1.0 ± 0.2 km/sec, and of a *b*-quality velocity to be 1.6 ± 0.4 km/sec. These errors are quite close to those estimated in the *RVC* itself.

VI. CONCLUSION

One observation with the photoelectric radial-velocity spectrometer, requiring only a few minutes' observing time, yields a result of practically the same accuracy as an *a*-quality catalogue velocity. It may be mentioned also that the total reduction time, from recorder chart to heliocentric velocity, is about 6 min per star, and the whole of the reduction procedure for forty stars occupies but one double page of a notebook.

The instrumental development reported in this paper is far from complete. An obvious further step is to extend the range of spectral types to which the radial-velocity spectrometer can be applied, by the construction of additional diaphragms based on the spectra of stars other than Arcturus. The amount of radial-velocity information implicit in a stellar spectrum is related to the mean gradient (taken without regard to sign) of the relationship between the light intensity and wavelength, i.e., of the spectrophotometric profile. Photographic observers are only too aware of the drastic reduction of this quantity as one goes to progressively earlier spectral types, and it is not certain that the spectrometer can usefully be applied to spectra earlier than about F0.

The determination of radial velocities is only one application of the technique of direct spectral matching, which is in principle much more versatile. Babcock (1955) has pointed out the possibility of measuring Zeeman separations by such a method. Again, the depths of the dips on the radial-velocity traces must be excellent measures of general line strength; they are strongly but not uniquely correlated with spectral type. One might hope for good correlations with type and with luminosity if the number of apertures in the diaphragm were reduced so that those remaining corresponded to well-informed choices of lines (segregated by, say, excitation potential; a modest start in this direction has been made by Scarfe [1966] with the Cambridge spectrometer). Diaphragms might in the future be constructed with a whole library of standard spectra side by side so that spectral types or other parameters could be determined by seeing which standard best fitted the observed spectrum. However, the application of the technique to radial velocities alone provides considerable observational opportunities.

Since January, 1966, the photoelectric radial-velocity spectrometer has worked as well as theoretical and intuitive considerations suggested it should, at the time that this project was begun. Although it is not the purpose of the present paper to describe the performance of the spectrometer in observations of faint stars, it may be said that an observing rate of 6–8 stars/hour is maintained to a limiting magnitude fainter than 9.0 even in the conditions of poor atmospheric transparency normal on "clear" Cambridge nights. The standard deviation of one observation has been shown to be about 1 km/sec on bright stars; it is near 2 km/sec at the ninth visual magnitude ($B \sim 10$ mag).

The way is therefore open in principle to the production of high-quality new velocities at a rate of several thousand a year. In practice this is not the case. The observations of bright stars described in this paper, plus a comparable number of observations of 8–10-mag stars, have not only occupied all the telescope time allocated to me this year, but more than half of each series has been observed in time generously donated out of their own allocations by research students J. B. Hutchings and J. F. Dymock. The principal stumbling block is the climate of Cambridge, which is more appropriate to the development of new instruments than to their use. For years funds have been sought to establish a modest outstation where Cambridge-developed techniques might be used on a worthwhile scale, but so far unfortunately without success. Admittedly the first half of 1966 was characterized by unusually poor observing conditions in England; but even at best, really good nights are rare, most clear weather comes in short spells unpredictable more than a few hours in advance, and a substantial observing program therefore requires very much more time and effort than it would at a good site.

This project would have been impossible without the co-operation and exceptional electronic skill of Mr. D. W. Beggs. Dr. E. H. Linfoot gave much assistance while the writer was learning digital computer programming; I am also indebted to the Director of the Cambridge Mathematical Laboratory for the use of the TITAN computer. The spectrometer was constructed, and has frequently been modified, in the Observatories' workshop by R. S. Overhill, R. B. Tomlin, R. H. Cullum, J. P. Hignell, and D. R. Palmer, who have shown great skill and patience in constructing the components of this equipment. Finally, it is a pleasure to thank Professor R. O. Redman for his longstanding interest in this project.

REFERENCES

Argue, A. N. 1963, *M.N R.A.S.*, **125**, 557.
Babcock, H. W. 1955, *Annual Report of the Director of Mount Wilson and Palomar Observatories, 1954/55*, p. 27.
Bayer, J. 1603, *Uranometria* (Augsburg).
Campbell, W. W. 1898, *Ap. J.*, **8**, 123.
Evershed, J. 1913, *Kodaikanal Bull.*, No. 32.
Fellget, P. 1953, *Optica Acta*, **2**, 9
Flamsteed, J. 1729, *Historiae Coelestis Britannicae* (London).
Griffin, R. F. 1961, *M.N.R.A S.*, **122**, 181.
———. 1966, *Observatory*, **86**, 145.
Griffin, R. F , and Redman, R. O. 1960, *M.N.R.A.S.*, **120**, 287.
Hartmann, J. 1904, *Ap. J.*, **20**, 338.
Hoffleit, D. 1964, *Catalogue of Bright Stars* (New Haven, Conn.: Yale University Observatory).
Huggins, W 1868, *Phil. Trans. Roy. Soc.*, **158**, 529.
Roman, N. G. 1952, *Ap. J.*, **116**, 122
Scarfe, C. D. 1966, *M N.R.A.S.*, **133**, 99.
Vogel, H. C 1892, *Pub. Ap. Obs. Potsdam*, No. 25.
Wilson, R. E. 1953, *General Catalogue of Stellar Radial Velocities* (Mount Wilson Observatory Papers, Vol. 8).
Wright, W. H. 1907, Lick Pub., **9**, 25.
Yates, G. G. 1948, *M N.R.A.S.*, **108**, 476.