RADIAL VELOCITY OBSERVATIONS OF BINARY STARS

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ABSTRACT

This review considers three main areas, leaving several others to be discussed in more detail in the contributed papers of this session.

1. The need for spectrographs and measuring instruments of great stability for long-term projects such as radial velocity observations of visual binary stars.
2. The use of cross-correlation devices, both analog (radial velocity scanners) and digital, for radial velocity measurement.
3. The use of comparison spectra impressed directly onto the starlight and of polarisation instruments as means to very precise radial velocities.

A. Introduction

In any discussion of spectroscopic techniques for the study of binary and multiple stars, the reasons for doing spectroscopy of these objects must first be considered. These reasons include spectral classification, detailed spectral analysis, and measurement of radial velocities, among others.

Spectral classification, normally done at low dispersion, is important for binary stars since the components are almost surely of the same age, but may well be of different mass and therefore at different evolutionary stages, which will be revealed by their location on the Hertzsprung-Russell diagram. The relative positions of wide pairs on the H-R diagram were studied some years ago by Petrie and Batten (1966), and more recently, classification work has been carried out by Abt and his colleagues (Abt et al. 1980, Abt 1981). However the task of classification may become very difficult when the stars are of similar brightness but are unresolved on the slit, and one has to record a composite spectrum. Early classification work on composite spectra was subject to large uncertainties, and indeed many objects were mistakenly classified as composite. Another problem arises when the two (or more) spectra are similar, and differ in radial velocity, but are not resolved at classification dispersion. The object may then quite undeservedly receive the "n" in its classification that would relegate it to the class of difficult-to-study broad-lined spectra.

Detailed spectral analysis of double stars is also important, but this subject, difficult enough for single spectra, becomes even more complex when the spectra are superposed. The problem was tackled for the nearly identical pair δ Equulei by Wehlau (1955), and more recently Stickland (1973) analysed the spectra of several Am pairs. But even small differences in magnitude or spectral type make the task almost hopeless. However, I shall not dwell further on this subject, nor on that of spectral classification, which will be discussed in more detail by subsequent speakers. Instead I shall devote the remainder of my paper to radial velocity work.

Radial velocities of binary stars are of course obtained primarily to determine orbital elements. When variable radial velocity is the only indication we have of binary nature, then the observations are confined to a single coordinate dimension, and cannot provide sufficient information to yield masses, even if both spectra are measureable. But when the pair can be resolved with the telescope, and radial velocity variations are detectable as well, then it becomes possible to study the motion in three dimensions, and to determine the distance accurately, and the masses and angular momentum vectors unambiguously. It appears that the latter quantities may be as significant in understanding the origin of binary and multiple stars as the masses have been shown to be for understanding their subsequent evolution. And it is by the combination of visual and spectroscopic data that these angular momenta are most reliably determined.

There are now so many techniques for radial velocity studies that I cannot cover them all in the time available for this review. I am therefore very glad to be able to leave the subjects of objective-prism radial velocities and the use of reticons and other highly sensitive digital devices to be dealt with in detail by subsequent speakers. My own experience is restricted to spectra of higher resolution than an objective prism provides, with the slower speed of observation that this resolution enforces. And although I should like to talk, briefly at least, about cross-correlation of digital spectra, I shall not discuss the problem of obtaining such data.

B. The Stability of Spectrographs

The precision with which radial velocities may be determined increases with the resolution of the spectrograph, at least until the resolution is so great that it contributes little to the broadening of spectral lines. For sharp-lined spectra this occurs only at the resolution of high-dispersion coudé spectrographs. And even at 1 Å/mm the spectrograph still normally contributes a little to the observed line width. So for radial velocity variations of small amplitude, such as are encountered in visual binaries, the high dispersion of a coudé spectrograph is almost a necessity.

But it is of course useful, and often essential, to pursue observations of such a system for many years in order to follow the radial velocity variations. Therefore one requires the spectrograph to give consistent results of high accuracy for many years. Coudé spectrographs have some advantages in this respect, since they are located apart from the telescope and are not subject to difficulties arising from flexure. Moreover they can with care be shielded from the defocusing effects of temperature variations.

However, a spectrograph which is used by many observers for various purposes suffers numerous changes in its configuration. With care it can be readily returned to a closely similar arrangement repeatedly. But it is easy for tiny changes to occur and to accumulate. Such a small effect, in this case the maladjustment of a collimator mirror which was frequently moved bodily across the room, led to a substantially increased scatter in the radial velocities of I.A.U. standard stars obtained over several years with the 6.5 Å/mm camera at the D.A.O. 1.2 m telescope. The problem was tracked down through a second effect of the same maladjustment, a slight asymmetry of the comparison lines, detectable only on the tracing of an oscilloscopic measuring machine. There remains a discrepancy of

0.6 km/s between that spectrograph and the I.A.U. standard velocity system, but it is now fairly constant and the scatter is reduced.

In an ideal world it would be possible to dedicate a few coudé spectrographs to accurate radial velocity work, in the same way that certain long-focus refractors are, or have been, dedicated to studies of binary stars, either visually or photographically. But in only two cases, to my knowledge, has this happened. The Cambridge 0.9 m telescope and coudé spectrograph have been used for some years almost exclusively by Griffin for his radial velocity work. And Beavers in Iowa seems embarked on a program with a similarly dedicated instrument. In Victoria, the 1.2 m coudé has been used predominantly, but by no means exclusively, for radial velocities.

The components of the long-camera spectrograph in Victoria are seldom moved, except for rotations of its mosaic grating. As a result this instrument has been found to give radial velocities, from photographic spectra with an ion-argon hollow-cathode comparison source, of good long-term stability. As an example, consider the thirteen observations of β Geminorum, an I.A.U. standard, listed in Table 1. They were obtained during four of the last five winters, and give a mean velocity of 3.21 km/s with a standard error per plate of 0.16 km/s. It should be noted that the typical exposure time is less than five minutes, and the constancy of the radial velocity indicates the relative freedom from guiding errors afforded by an image slicer for exposures of such short duration. As a second example, Figure 1 depicts radial velocities of the primary component of ζ Herculis, obtained initially by Petrie, and since his death largely by the author. These velocities now cover just over half of the 34-year cycle, and can be fitted with a Keplerian velocity curve with elements similar to Berman's (1941). The r.m.s. scatter is just under 0.25 km/s. No special care was put into the obtaining and measurement of these spectrograms, and the result is indicative of the instrument's stability since the date of its first use in 1962. No indication is given of a third component of the system, at least attending the primary. Such a component has been suggested several times before, for example by Baize (1976), but these data and those of Lippincott (1981) provide strong evidence that none exists.

It is also important, of course, to have reliable measuring machines, but the long-term stability is not so critical since all the spectra can be measured in a short time. Those of ζ Herculis, for example, were nearly all measured in the summer of 1980.

C. Radial Velocity Scanners

In the 1960's, Griffin (1967) showed that it was possible to obtain radial velocities efficiently directly at the telescope. Instead of being recorded for later use the star's spectrum is allowed to fall on a diaphragm or mask placed in the focal plane. This diaphragm consists of a series of apertures in the rest positions of a large number of spectral lines, and thus mimics the stellar spectrum over a modest range of spectral types. The stellar spectrum is scanned in wavelength, and when it is in register with the diaphragm, absorption lines fall on the apertures, and a minimum amount of light is transmitted. This light is collected by a large lens and brought together on the cathode of a photomultiplier tube. Thus all other spectral information is sacrificed in order to provide rapid radial velocity observations.

With his earliest instrument, Griffin scanned slowly once along the spectrum of each star, recording the output on a chart. However, more recently it has been found possible to scan repeatedly and to accumulate many scans digitally with a computer, thus smoothing out the effects of guiding errors and of the slower types of seeing variations. Seeing fluctuations which are fast compared with the scan rate (typically one second per scan) are still a nuisance. Instruments of this sort have been built by Griffin and Gunn (1974) at Palomar, by Slovak et al. (1979) at McDonald, and by Beavers and Eitter (1977) at Fick Observatory. The scanner at the D.A.O., originally built by Stilborn et al. (1972), has been converted to photon-counting and digital recording by Fletcher.

With a high-dispersion spectrograph, the amount of information that can be recorded, and the limiting magnitude, are set to a considerable extent by the difficulty of focusing a substantial length of spectrum onto a photocathode, and the large, and therefore noisy, photocathodes that must be used. A larger spectral range may be covered if an echelle is used as the disperser, together with a mask that is two-dimensional and transmits several orders. The relative merits of such a device were discussed by Hearnshaw (1977) and its inherent difficulties by Griffin (1977). Despite these difficulties, however, an instrument incorporating an echelle, CORAVEL, has been successfully built by Baranne et al. (1979), and has been shown to yield high-quality radial velocities. A similar instrument is in operation at ESO.

Scanners are limited by the modest range of spectral type to which the mask can be matched. The minimum or dip in the transmission, when the stellar spectrum and the mask are in registration, weakens beyond this range and is lost. Baranne et al. (1979) have managed to use the CORAVEL mask, which matches the spectrum of Arcturus (K2III), from late F to early M. And the difficulty has been eased at the D.A.O. by using two masks, one for K stars (matching Arcturus) and the other for F stars (matching Procyon). Stars of type G may be observed with either mask, and at present McClure, H. Harris and the author are still assessing the possibility of any systematic difference between the masks for these stars. For stars of earlier type, the paucity of lines, the domination by strong lines of hydrogen, and the frequency of broadening by rotation have so far prevented the use of scanners. It is possible with the Procyon mask to observe some stars of type Am, but stellar rotation so readily broadens the minimum that for $v_e \sin i > 30$ km/s, radial velocities are very difficult to measure (Poeckert, private communication). However, Baranne et al. (1979) indicate that, instead, rotation velocities can be measured with CORAVEL, up to about the same limit in $v_e \sin i$, 30 km/s. Fletcher is looking into various ways to extend the technique to early-type stars.

The work of Griffin (1972), Gunn and Griffin (1979), Baranne et al. (1979) and McClure (private communication) has clearly shown that radial velocities of accuracy close to ± 1 km/s can be obtained for stars as faint as 12th or 13th magnitude. This is a very substantial improvement on the magnitude which can be reached photographically at comparable accuracy. It seems, however, that it is difficult to reduce the uncertainty of an individual observation much below 0.5 km/s, even for bright stars, whereas as I have already shown, an uncertainty no larger than 0.25 km/s can be achieved photographically for such objects. Part of the difference may be attributable to systematic shifts from night to night, which can be reduced by care in setting the instrument up, as our experience has shown. The limit, in precision at least, has not yet been reached. There remains the problem of systematic differences between observatories, with which photographic radial-velocity workers have had over eighty years' experience, but which has been a little neglected by them recently. Now that several others besides Griffin are beginning to accumulate long runs of scanner observations, it is time to address this problem anew. In the process it may become necessary to reconsider the I.A.U. system of standard velocities, a task on which a useful first step has been taken by Beavers et al. (1979).

The usefulness of scanner velocities for binary star work has been amply demonstrated by Griffin in his long series of papers in "The Observatory", each yielding a new spectroscopic orbit, in most cases of long period (for a spectroscopic binary). The majority of the stars are giants whose companion is not detectable in the spectrum, and so many new orbits are now available that my paper (Scarfe 1970) on the mass functions of these objects is now woefully out of date.

The scanner is also advantageous for measuring the radial velocities of faint components, since it combines the information from many lines. This is demonstrated by the case of 1 Gem B for which Griffin and Radford (1976) obtained a satisfactory short-period orbit from scanner observations. By contrast in my photographic spectra taken at about the same time (some of which were used by Griffin (1980) for his article in Sky and Telescope) the spectrum of 1 Gem B is very hard to measure reliably. With the D.A.O. scanner it has, moreover, been possible to measure, in under an hour, all three components of such objects as HD 100018, studied by Petrie and Batten (1969), and HD 202908 (Fekel 1981). It is not yet clear whether or not one can resolve as small velocity differences as one can photographically, in the case of double or multiple spectra. But I hope to address this problem in the current season, using δ Equulei, for which Hans et al. (1979) showed that pair blending is important for $\Delta V < 15$ km/s in photographic spectra taken with the same optics as the scanner uses.

D. Digital Cross-Correlation Techniques

The transmission function that is recorded as the mask of a radial velocity scanner is moved in wavelength along a stellar spectrum is essentially a cross-correlation function between that spectrum and the artificial spectrum represented by the mask. It is possible, however, to replace the artificial spectrum with a real standard one, and to use a computer to perform the cross-correlation digitally. This can be done with digitized photographic spectra, or with spectra originally recorded digitally by one of several devices currently in use, for example the image photon-counting system (IPCS) of Boksenberg (1972). Two versions of this technique have been published, respectively, by Da Costa et al. (1977) and by Sargent et al. (1977); the latter has been modified somewhat by J. Rose (Dressler 1979).

In both of these methods the spectra must be manipulated prior to performing the cross-correlation. In general, they must be flattened, the continuum removed, and the ends trimmed so that exactly the same wavelength regions in the unknown and standard spectra are cross-correlated. In the approach of Da Costa et al., the resulting spectra are expanded in a Fourier series in order to allow filtering; this permits the removal of any low-frequency components due to imperfect continuum subtraction, as well as high-frequency noise. The cross-correlation function is then obtained by inverting the Fourier transformation of the product of the two series. This approach has been applied successfully at Mt. Stromlo to radial velocities of late-type stars in globular clusters and elsewhere. But the small size of the detector limits the useable wavelength range and does not readily permit sufficient radial-velocity information to be recorded for studies of early-type objects, as my own limited experience with it at Mt. Stromlo indicated.

The approach of Sargent et al. (1977) differs somewhat in that its primary purpose is to determine velocity dispersions from galaxy spectra, with the radial velocity being of secondary importance. The standard spectrum is that of a star of the galaxy's integrated spectral type, which of course cannot precisely resemble the galaxy's spectrum. The latter is however assumed to approximate the convolution of the spectrum of the standard star with a Gaussian broadening function whose width depends on the velocity dispersion and whose centroid yields the radial velocity. In this approach, therefore, the ratio of the discrete Fourier transforms of the galaxy and star spectra is found, and fitted by a broadening function. Because the ratio of the transforms is inevitably noisy, it must be fitted by the use of a X^2 distribution whose most satisfactory form is given by Dressler (1979).

This technique has proved very useful in determining velocity dispersions, but due in part to wavelength instabilities in the IPCS, not for radial velocities accurate by the standards of stellar astronomy. Such instability appears to be a problem with many digital detectors, and needs to be carefully checked by the observer using a standard source in the dome. However, if this is done (as it must be for photographic and scanner work as well, of course) there is no reason in principle why the technique should not give excellent results, particularly since the spectra often have very high signal-to-noise ratios, compared with photographic spectra. Moreover they are usually recorded on magnetic tape and can be used subsequently for other purposes. This is not the case for scanner observations; only the transmission function can be retained, although this alone may be useful for finding rotational velocities and metallicities (Baranne et al. 1979).

Since the technique of Sargent et al. (1977) incorporates a broadening function, it seems to offer some hope of handling the radial velocities of more rapidly rotating stars, including perhaps those of early type if a large enough wavelength range can be accommodated by the detector. The rotational broadening function would of course not be Gaussian, and its transform would presumably involve Bessel functions as discussed by Deeming (1977). If this can be done successfully, it might permit a substantial improvement in the accuracy of radial velocities of rapidly rotating late A and F stars, where rotation makes line-blending very severe, and simultaneously yield rotational data.

Finally it should be mentioned that Morbey has used the very simple direct method of obtaining radial velocities from complex spectra by adding the profiles of several features together to reduce the noise. This method was applied by Morbey et al. (1977) to HD 165590 (ADS 11060), a double-lined triple system in which both spectra are of type G, and the brighter star is rotating rapidly, producing a very awkward spectrum to measure by conventional means.

E. Very Precise Radial Velocities

Among the techniques discussed so far, the highest accuracy seems to have been achieved by direct photographic spectroscopy, and oscilloscopic measuring engines. Over a long period, an r.m.s. scatter of 0.25 km/s has not been surpassed, although 70 m/s has been obtained in a limited situation by Petrie and Fletcher (1967).

Two approaches appear to be leading to substantial improvements in precision, and perhaps in accuracy as well. The first is to avoid the differences in grating illumination that are inevitable when a comparison spectrum is exposed separately from that of the star, by using instead a spectrum superposed directly onto the stellar spectrum. This was first attempted by Griffin and Griffin (1973) who used telluric water vapour lines in the extreme red. But these are too weak, numerous and sensitive to changes in atmospheric pressure to be really satisfactory. However, Campbell and Walker (1979) have found that a better comparison spectrum is that of gaseous hydrogen fluoride. They pass the stellar beam from the telescope through a cell filled with this gas, which superposes several strong, well-separated lines onto the stellar spectrum in the near infrared. Radial velocities with a precision of 10 m/s can be obtained if the spectrum is recorded digitally with very high signal-to-noise ratio. Hydrogen fluoride is of course a very unpleasant and difficult substance to handle, being corrosive to glass and reactive with human tissue. Moreover it polymerises at temperatures below 70°C and must therefore be kept in a sealed, heated container. Fortunately it produces strong lines at low column densities and the absorption cell can therefore be maintained below atmospheric pressure, thus reducing the amount that would escape if any leak should develop. HF absorption cells are now in use by Walker in Victoria and by Campbell at the Canada-France-Hawaii Telescope.

The second approach is that of Serkowski and his colleagues at the Lunar and Planetary Laboratory (Serkowski 1976, Serkowski et al. 1979). Several rather similar instruments have been constructed, at least partly in an attempt to detect small radial velocity variations of stars, caused by planetary companions. One such device (Serkowski 1976) uses a retarder and a quarter-wave plate to impose on the stellar beam a polarisation whose position angle varies rapidly with wavelength. Determination of this position angle suffices to fix very accurately the wavelength at any point of the detected stellar spectrum. Thus radial velocities relative to other nearly identical stars, or to the same star at other epochs may be determined with high precision. A more recent instrument (Serkowski et al. 1979) involves a Fabry-Perot interferometer, and an echelle-grism post-disperser.

To obtain with such instruments the accuracy which their precision indicates they can in principle achieve, over the long term necessary for binary star work, will place even more stringent requirements on the stability of the instruments themselves, and in the case of HF cells, on the spectrographs with which they are used, than has been necessary hitherto. It will for example be necessary to improve the temperature control of these instruments considerably. Absolute radial velocities of this accuracy, as distinct from relative ones, are an extraordinarily difficult problem, requiring standard wavelengths of stellar and comparison lines known to an accuracy of one part in 10^8.

In addition, atmospheric motions in the stars themselves may make any such velocities unrepresentative of the centre of mass of a star. This problem was raised by Huang (1973) and discussed in some detail by Dravins (1976) who showed that such motions may cause the measured radial velocity to differ from that of the centre of mass by ± 0.5 km/s. It may be noted that the rather smaller scatter for ζ Herculis and β Geminorum discussed earlier indicates that any effect of such motions has been constant to at least ± 0.25 km/s over the intervals covered by the observations. Moreover, a partial solution to the problem of distinguishing random atmospheric motions from the systematic motion of the whole star has been indicated in recent work by Deming (1980). As can be readily appreciated, however, the combined effects of atmospheric motions and limb darkening make any velocity determined, as it must be, from the integrated light of a star, hard to relate with certainty to the absolute radial velocity of its centre of mass.

F. Summary

Techniques now available provide greater opportunity than in the past to follow the small slow radial velocity variations common in binary and multiple stars. Conventional spectrographs are capable of long-term accuracy of 0.25 km/s. Radial velocity scanners, and possibly cross-correlation techniques too, permit the extension of velocities approaching this accuracy to much fainter than can be reached photographically. Substantial increases in precision seem to be possible using polarisation techniques or comparison spectra imposed on the stellar beam directly, but much work remains to be done to exploit these new methods to their full extent in the study of binary and multiple stars.

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DISCUSSION

ABT: Have you tried a scramble technique to remove guiding errors?

SCARFE: No, we have not, but the image slicer does that to some extent, in that it provides a partial scrambling.

WHITE: Do you mean to indicate that the radial velocity meter has served out its usefulness?

SCARFE: I think it is a very useful instrument, although it may not be quite as accurate as some other methods. It has the virtue of being very fast and getting accurate velocities at quite faint magnitudes, so I think it is going to continue in use for some time.

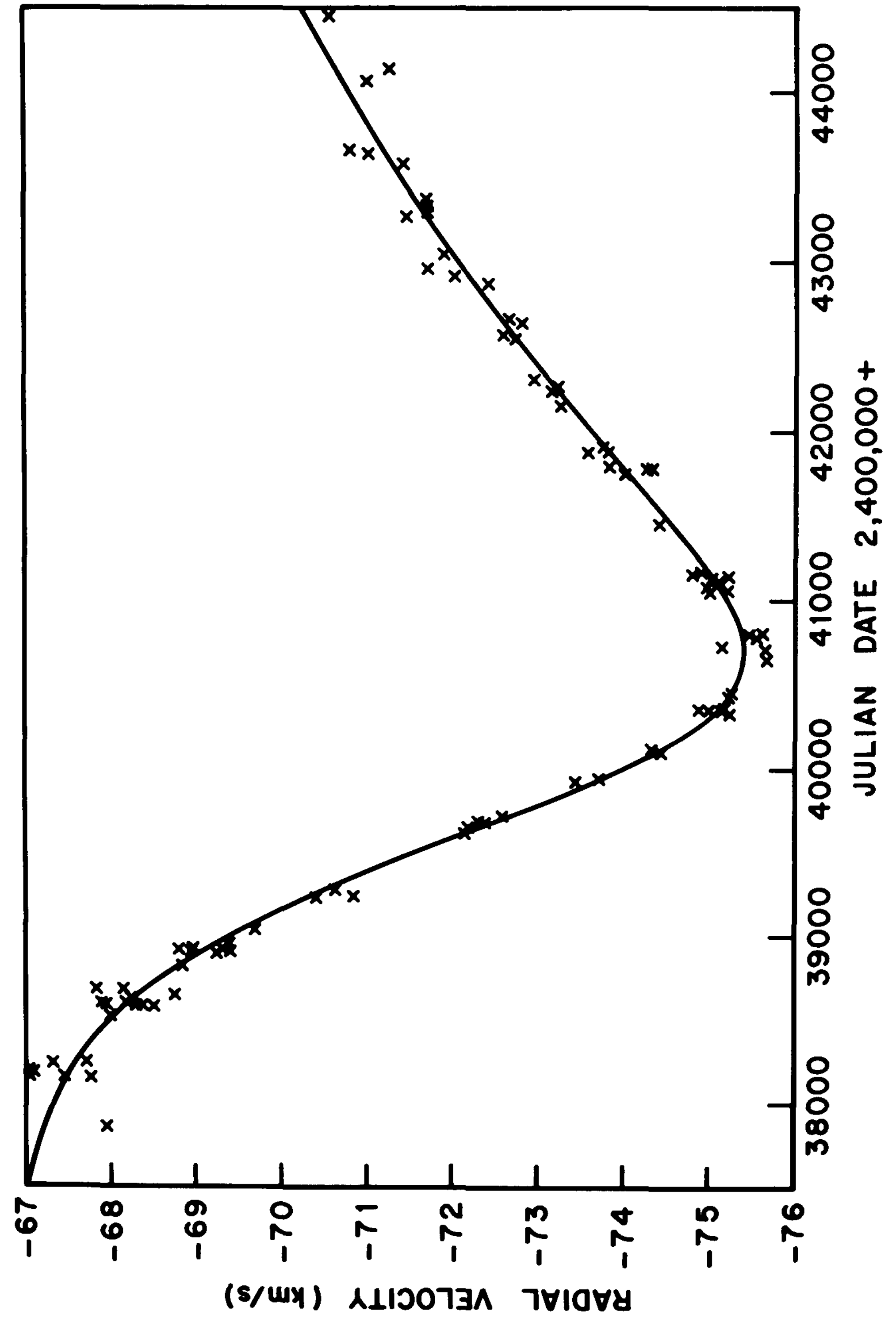
TABLE 1

RADIAL VELOCITIES OF β GEMINORUM

DATE		VELOCITY
1976	Nov. 28	3.62
1977	Mar. 13	3.17
	Oct. 13	3.35
	Dec. 11	3.20
1978	Feb. 11	2.98
	Mar. 4	3.38
	Mar. 19	3.22
1979	Oct. 2	3.17
	Nov. 20	3.03
1980	Mar. 22	3.11
1981	Jan. 14	3.22
	Feb. 11	3.18
	Apr. 13	3.12
	Mean	3.21 km/s
	Ext. m.e. (per plate)	0.16 km/s
	Int. m.e. (r.m.s.)	0.05 km/s

Figure Caption

Figure 1. Radial velocities of ζ Herculis A obtained from D.A.O. coudé spectrograms, 1962-1980. The curve is from a Lehmann-Filhés least-squares fit with the period fixed.


RADIAL VELOCITY (km/s)
-67
-68
-69
-70
-71
-72
-73
-74
-75
-76
JULIAN DATE 2,400,000+
38000
39000
40000
41000
42000
43000
44000