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RADIAL VELOCITIES AND POSITIONS FROM OBJECTIVE PRISM PLATES

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RESUMEN

Placas de prisma objetivo son utilizadas para determinar posiciones, velocidades radiales relativas aproximadas, magnitudes y tipos espectrales para 10 053 estrellas en una zona austral. El catálogo preparado es la primera parte de una búsqueda extensa que sirve como fuente para posibles estrellas de alta velocidad, y que puede contribuir al estudio de las características cinemáticas de la Vía Láctea.

ABSTRACT

Objective prism plates are used to determine positions, approximate radial velocities, magnitudes, and spectral types for 10 053 stars in a selected southern zone. The catalogue produced is the first part of an extensive survey which serves as a finding list for possible high velocity stars, and which may contribute to the study of the kinematic characteristics of the Milky Way Galaxy.

Key words: POSITIONS – RADIAL VELOCITIES – MAGNITUDES – SPECTRAL TYPES

I. INTRODUCTION

The statistical analysis of space motions of different types of stars provides important arguments for the theories of stellar evolution as well as evolution of galaxies. The tangential components of space motions come from general proper motion surveys providing samples which are not biased by a previous selection of types of stars. This is not the case for the radial component of space motions. Many of the known high radial velocity stars were selected for a spectroscopic study on the basis of their spectral types, since the latter indicated that the respective stars belong to the Population II. To overcome this bias it is evidently desirable to undertake a radial velocity survey in at least a number of selected and strategically located fields.

The feasibility of determining radial velocities using objective prism plates was recognized as soon as the latter came into use. Schwarzschild (1913) was the first, though, to look into the mathematical details of the method which consisted of either comparing a direct plate (i.e., without prism) with a prism plate, or of intercomparing two prism plates with opposite dispersions. He deduced the nature of the field distortion and its relations to the particular characteristics of the prism. It is the large and complicated distortion which prevented astronomers for a long time from making extensive use of the method. An interesting alternative method was analyzed by McCuskey (1936) who impressed an absorption feature of fixed wavelength on the spectra using a neodymiun filter in front of the plate. The method failed due to the asymmetric structure of the absorption band.

Fehrenbach (1947) gave the method of objective prism velocities a new impulse by designing a three-component prism which removes most of the distortion terms of a single prism. Due to its large weight and high cost only few Fehrenback-type prisms are in use today. In view of this, the theory of the simple prism was rediscussed by Stock and Upgren (1968). Subsequent numerical tests based on their theory showed that with a proper orientation of the prism most distortion terms vanish, while the remaining ones take a simple mathematical form. Thus the field was opened again for a general radial velocity survey using existing telescopes and prisms.

Recently Gieseking (1976, 1977, 1980, 1981) developed a new method using a Fehrenbach-type prism, aiming at the maximum possible accuracy. Since his method requires that the same spectral lines are measured in all stars, a restriction to certain spectral types is obviously necessary. On the other hand, Gieseking's method permits the detection of stars with variable radial velocity.

For the planning of an extensive radial velocity survey a decision had to be made with respect to the number of exposures on a single plate. Similar to the Fehrenbach method both exposures with opposite dispersions can be photographed on the same plate. Naturally this requires exact knowledge of the field displacement caused by the prism. The double exposure method has the advantage that distortions due to the emulsion are practically eliminated. On the other hand, the sky background is increased, as well as the number of overlapping spectra. The two-plate method, i.e., the two exposures on separate plates, permits one to reach fainter magnitudes, and reduces the loss due to overlap. An equally important difference between the two methods relates to the available measuring equipment. In the two-exposure method the radial velocity is derived from differential measurements, while the coordinates themselves have only a secondary importance. Also, practically any type of measuring engine may be used. On the other hand, the two-plate method is practical only if a stereoscopic measuring engine is available. One such machine, a Zeiss PSK2, was acquired by the Venezuelan National Research Council (CONICIT) in 1972, and a second one in 1974.

The choice of fields for a radial velocity survey depends principally on what one wishes to do with the radial velocities once they are available. Peralta (1973) showed that the range of radial velocities observed in a certain area may be expected to depend on its galactic latitude and longitude. In fact, this dependence of the radial velocity range on the galactic coordinates contains information on a number of kinematic parameters of the Galaxy, and more so, if this range is determined for different types of stars. This calls for a scheme similar to the Kapteyn areas. However, a different plan was made for the project in view of the fact that the first telescope available for it, was the Schmidt telescope on Cerro Tololo, equipped with a four-degree prism. The zone between the southern declinations –30° and –35° passes practically through the zenith of the observatory, and at the same time passes near the galactic center and near one of the galactic poles. To this we may add that for observing it is very practical if the telescope remains permanently at the same declination.

Objective prism plates may also be used for the determination of stellar positions, as was shown by the author (Stock 1978). Such positions may even be of higher accuracy than those derived from direct plates. Thus one single set of plates can provide information on coordinates as well as radial motions.

II. THE OBSERVATIONS

The plate material was obtained with the Curtis Schmidt telescope on Cerro Tololo, equipped with a four-degree prism. The combination yields a dispersion of approximately 225 A mm^{-1} at H-gamma. The plate material is in all cases Kodak IIaO, and the exposure time 20 minutes. The spectra were widened to 0.17-mm. Details of the plates are given in Table 1.

TABLE 1

THE PLATE MATERIAL

Plate Number	Date		R.A. (1950.0)	Dec. (1950.0)	Prism Apex
21554	1978 April	12	12^{h}00^m	– 28°0	N
21555	”	12	12 00	– 28.0	N
21556	”	12	12 00	– 28.0	S
21557	”	12	12 00	– 28.0	S
21541	1978 April	11	12 20	– 28.0	N
21542	”	11	12 20	– 28.0	N
21543	”	11	12 20	– 28.0	S
21544	”	11	12 20	– 28.0	S
21510	1978 April	9	12 40	– 28.0	N
21511	”	9	12 40	– 28.0	N
21512	”	9	12 40	– 28.0	S
21513	”	9	12 40	– 28.0	S
6850	1970 June	2	12 40	– 32.5	N
6851	”	2	12 40	– 32.5	N
6852	”	2	12 40	– 32.5	S
6853	”	2	12 40	– 32.5	S
6843	1970 June	1	13 00	– 32.5	N
6844	”	1	13 00	– 32.5	N
6845	”	1	13 00	– 32.5	S
6854	”	1	13 00	– 32.5	S
6823	1970 May	29	13 20	– 32.5	S
6824	”	29	13 20	– 32.5	S
6825	”	29	13 20	– 32.5	N
6826	”	29	13 20	– 32.5	N
6836	1970 May	30	13 40	– 32.5	N
6837	”	30	13 40	– 32.5	N
6838	”	30	13 40	– 32.5	S
6839	”	30	13 40	– 32.5	S
6855	1970 June	2	14 00	– 32.5	S
6856	”	2	14 00	– 32.5	N
6857	”	2	14 00	– 32.5	N
6858	”	2	14 00	– 32.5	N
6827	1970 May	29	14 20	– 32.5	N
6828	”	29	14 20	– 32.5	N
6829	”	29	14 20	– 32.5	S
6830	”	29	14 20	– 32.5	S
6864	1970 June	3	14 40	– 32.5	S
6865	”	3	14 40	– 32.5	S
6866	”	3	14 40	– 32.5	N
6867	”	3	14 40	– 32.5	N
6868	1970 June	3	15 00	– 32.5	N
6869	”	3	15 00	– 32.5	N
6870	”	3	15 00	– 32.5	S
6871	”	3	15 00	– 32.5	S
21577	1978 April	13	15 20	– 31.5	S
21578	”	13	15 20	– 32.5	S
21579	”	13	15 20	– 32.5	N
21580	”	13	15 20	– 32.5	N

III. THE MEASUREMENTS

A Zeiss PSK2 stereocomparator was used for scanning the plate pairs and for measuring every suitable pair of spectra. In each spectrum pair as many lines of a given list as were well defined were measured. Table 2 lists the lines used. In view of the reduction procedure to be used only those lines were measured which were well defined in both spectra, although we have reduction methods available which can make use of measurements in one spectrum only. The machine permits measurements with an accuracy of 0.001 mm, although a typical setting accuracy is more like 0.003 mm.

Along with the coordinate measurements, the spectral type and, if possible, the luminosity class of each object was estimated, as well as the photographic density of each spectrum.

TABLE 2

LINES USED FOR RADIAL VELOCITY AND POSITION MEASUREMENTS

No.	Wavelength (A)	Name	Element	B_{00}	Vel. Factor	Weight	Spectral type range
1	4861	Hβ	H	6.9492	21210	1	B-G
4	4340	Hγ	H	3.7141	9170	2	B-G
5	4305	G-band	Fe	3.4429	8970	2	G0-K
7	4227	...	CaI	2.8145	8530	4	G7-M
9	4102	Hδ	H	1.7102	7830	3	B-G
11	3970	Hξ	H	0.3924	7120	2	B-A1
12	3968	H	CaII	0.3807	7110	4	G3-M
13	3934	K	CaII	0.0000	6920	4	A-M
14	3889	H-8	H	– 0.5008	6680	3	B-F
15	3835	H-9	H	– 1.1325	6400	3	B-F
16	3798	H-10	H	– 1.6006	6200	3	B-F
17	3771	H-11	H	– 1.9500	6060	3	B-F
18	3750	H-12	H	– 2.2245	5960	3	B-F
21	3748	...	Fe	– 2.2564	5950	3	K-M
22	3735	...	Fe	– 2.4326	5880	3	K-M
23	3721	...	Fe	– 2.6268	5810	3	K-M
24	3707	...	Fe	– 2.8206	5740	3	K-M

The total number of stars measured on a given plate pair varied from about 400 to about 1600, depending mostly on galactic latitude, and somewhat on the not very uniform limiting magnitude of the plates.

The plates were oriented such that the Y-coordinate coincided with the direction of the dispersion. The PSK2 permits to place the origin of the coordinates anywhere in the field. Thus in each case the K-line of a star located close to the center of the plates was chosen as origin, although in the reduction process the origin has to be transferred to the geometrical center of the plates.

IV. REDUCTION OF THE RADIAL VELOCITIES

The reduction procedure to be used to derive the radial velocities is essentially a refinement of the method proposed by Stock and Osborn (1980, hereafter Paper I). Let us consider for a moment the measurements of one given spectral line only. The difference between the two Y-measurements will vary from star to star. The variation contains in the first place a systematic component, due to the distortion of the field caused by the prism. In addition, apart from measuring errors and erratic displacements due to emulsion distortion, there will also be a component due to the radial velocity of the respective objects. The systematic part we describe by a polynomial of the form

$$\Delta Y(X, Y) = \sum_{ij} B_{ij} \bar{X}^i \bar{Y}^j \qquad (1)$$

where $\bar{X}$ and $\bar{Y}$ are obtained by averaging the x- and y-measurements from both plates for every star. The degree of the polynomial is defined by N, such that

$$i = 0, 1, 2, 3 \ldots N$$

$$j = 0, 1, 2, 3 \ldots N$$

with

$$0 \leqslant i + j \leqslant N \ .$$

Experience shows that N = 3 is sufficient for the material on hand.

Now we have to consider that we are dealing with several spectral lines. This means in the first place that the coefficients B_{ij} in equation (1) are actually functions of wavelength. Numerical tests as well as empirical data show that these coefficients are actually linear functions of the refractive index, i.e.,

$$B_{ij}(\lambda) = c_{ij} + d_{ij}\, n(\lambda) \qquad (2)$$

As was shown in Paper I, many of the coefficients c_{ij} and d_{ij} vanish with a proper prism orientation, while

$$c_{02} = c_{20} = \text{prism constant},$$

$$d_{02} = d_{20} = \text{prism constant},$$

and

$$B_{00}(\lambda) = c_{00} + d_{00}\, n(\lambda) \ . \qquad (3)$$

The last equation represents twice the dispersion curve of a single spectrum at the origin of the coordinates.

Combining equations (2) and (3) we may write

$$B_{ij}(\lambda) = e_{ij} + f_{ij}\,\overline{B_{oo}}(\lambda), \qquad (4)$$

where $\overline{B_{oo}}(\lambda)$ can be an approximate value, since f_{ij} is in all cases a small number. With N = 3 the entire system of unknowns consists of ten values for e_{ij} and ten values for f_{ij}.

Strictly speaking, the values of X and Y in equation (1) may also depend slightly on the wavelength. This effect, however, is negligible for the purpose of deriving radial velocities, when the two plates are well oriented (the spectra on the two plates are parallel to each other). It will be taken into account for the derivation of positions.

At a rather early phase of the work it was discovered that the B_{oo}-values were not only a function of the wavelength but for several lines seemed to depend on the spectral type also. A typical example is given in Figure 1. This spectral type dependence may have several sources. Some lines may actually be blends, with the contribution of each component depending on the spectral type. Likewise, the apparent position of a line may be altered by the gradient of the continuum. The latter, naturally, is a function of the spectral type. This could cause also a magnitude or photographic density dependent alteration of the apparent positions of lines. No such effect, however, was detected. This is probably due to the fact that lines were measured only in a restricted range of photographic densities of the continuum. For faint stars mesurements were made in the blue part of the spectrum, while for over-exposed stars only lines in the violet or ultraviolet were measured. The spectral type dependence of the B_{oo}-values was studied in great detail, using the entire material on hand, resulting in a correction table which line by line and star by star was applied to equation (1). These corrections we shall call E(λ,Sp), where Sp stands for the spectral type. Average B_{oo}-values are given in Table 2.

If we now combine equation (1) with equation (4) we obtain

$$\Delta Y(\overline{X},\overline{Y}) - E(\lambda,Sp) = \sum_{ij=0}^{N} [e_{ij} + f_{ij}B_{oo}(\lambda)]\,\overline{X}^i\overline{Y}^j \quad . \qquad (5)$$

The values of the coefficients e_{ij} and f_{ij} may be determined by least squares methods. Every star contributes to the solution with every line measured in its spectra. Considering that we have on the average about 1000 stars per plate, and that we measured on the average about four lines in every spectrum, we conclude that we have enough entries to calculate significant values of the twenty unknowns.

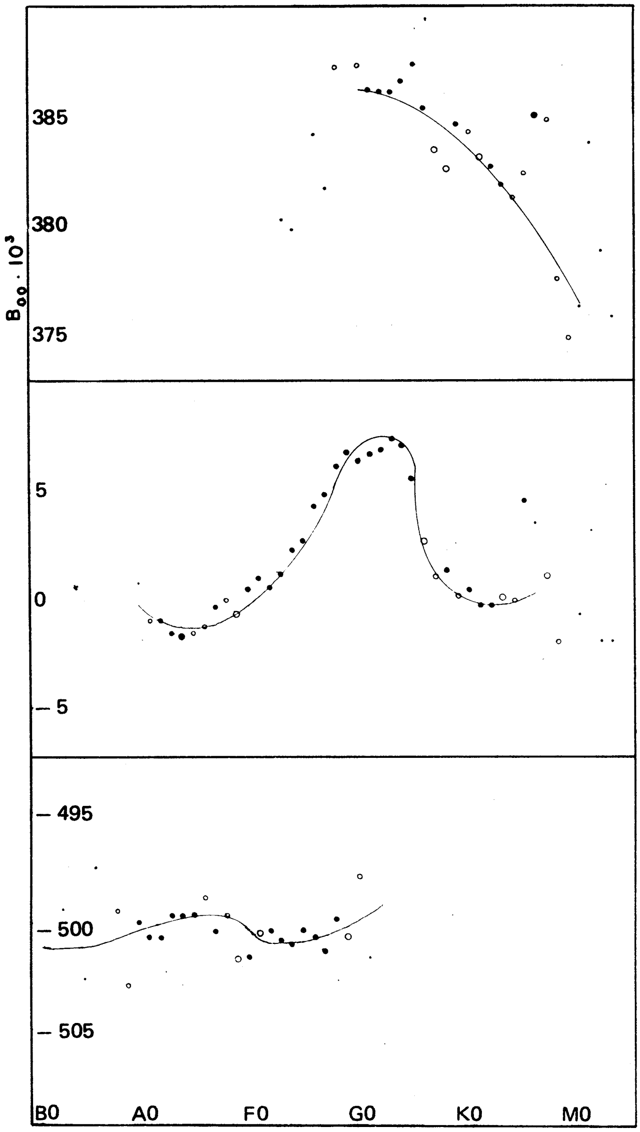

Fig. 1. Variation of the location of a measured spectral line with the spectral type. Small dots are used for five or less determination, open circles indicate from six to fifty determinations, and filled circles are used when more than fifty determinations were available.

Once the coefficients have been determined we can proceed to calculate radial velocities for every star. For this purpose we calculate the difference between the measured Y-values and those predicted by the polynomial in equation (5). These residuals ΔΔY are converted into velocities in km s^{-1} by multiplying them by the velocity factor V_f. The latter can be derived from the dispersion curve

$$\lambda - 1993.5 = \frac{41501.7}{21.3955 - B_{oo}(\lambda)} \qquad (6)$$

which was determined from the B_{00}-values and wavelengths given in Table 2. The velocity factor is also listed in Table 2.

Equation (6) is applied separately for every measured line. Thus for stars for which several lines were measured radial velocities are separately calculated, and the results averaged. A statistical analysis of the residuals, i.e., the differences between the average velocity and the individual velocities, revealed two facts: In the first place, the mean rms residuals are different from line to line. This led us to assign weights to the different lines. These weights are listed in Table 2. Also we found that the mean residual depends on the magnitude of the stars, as shown in Figure 2.

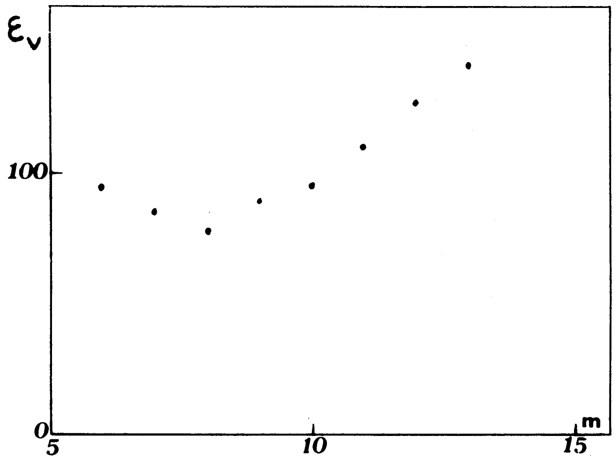

Fig. 2. The mean rms-error of the radial velocities per unit weight as function of the apparent magnitude.

The weights are taken into account in the least square solution for equation (5).

Finally it should be pointed out here that the radial velocities thus derived are relative velocities. Here "relative" means that the velocities are for each plate pair relative to the average radial velocity of all stars which contributed to the solution of equation (5), taking into account their number of lines with their respective weights. In fact even a systematic variation of the average velocity across the field would not appear in the final data since such an effect would be absorbed by the coefficients. In view of the low accuracy of our velocities, however, such effects do not seem to have any importance. Thus the main difference between our velocities and slit velocities is caused by the solar motion with respect to the local standard of rest. A comparison of our velocities with slit velocities is shown in Figure 3. The slit velocities were taken from Abt and Biggs (1972), and from MacConnell, Stock, and Alvarez (1979).

Some of the plates used for this work have recently

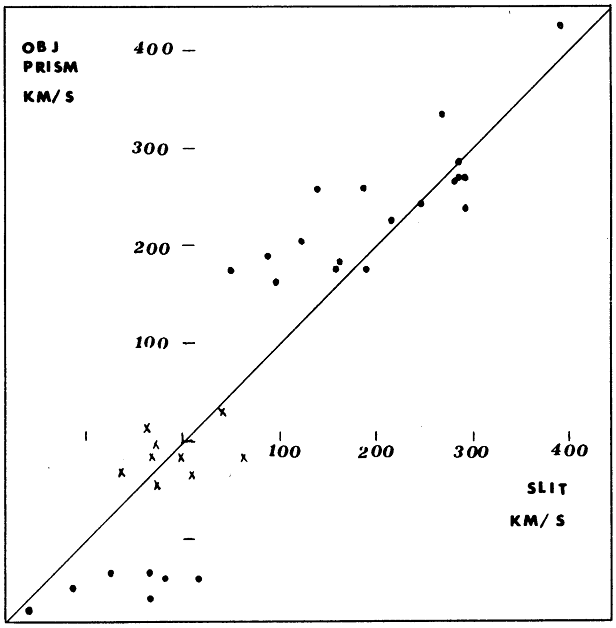

Fig. 3. Comparison of the objective prism velocities (corrected for solar motion) with slit velocities. Dots are stars observed by MacConnell *et al.* (1979). The stars for which a radial velocity is given by Abt and Biggs (1972) cluster around zero velocity; hence only a few are shown on the graph (crosses).

been remeasured by Weiss, Upgren, and Dawson (1981) using the PDS measuring machine of the Kitt Peak National Observatory. Their results not only confirm the feasibility of such a procedure, but also demonstrate the superiority of the automatic measuring engine.

V. REDUCTION OF THE POSITIONS

For every star 2n X- and Y-coordinates are available, if n lines were measured in its spectra. The problem we wish to solve is to find the best average X and Y from all coordinates on hand. When both spectra are strictly parallel and of the same dispersion, then line by line average of the coordinate pair will lead to the same average X and Y, apart from measuring and other accidental errors. However, the spectra are not necessarily parallel. In fact, the prism theory shows that the direction of the dispersion will vary slightly across the field. The same is true for the dispersion. For every plate pair these effects were analyzed and both the dispersion and the tilt of the spectra expressed in the form of polynomials as function of the coordinates and B_{00}-values. In this form the average X- and Y-coordinates found in a given spectrum for a given line can be reduced to the average position which would be obtained for an arbitrarily chosen line, in our case the K-line.

Coordinates obtained in the way described above may be handled in the same way as measurements on direct plates would be handled, except that we have to take into account field distortion terms caused by the prism. Nevertheless, the prism theory shows that the principal distortion term, described by the coefficients c_{02} and c_{20} of the previous chapter, drops out, while on the other hand a large linear term in the direction of the dispersion is created. The latter will be allowed for in the reduction.

For the conversion of the X- and Y-coordinates into equatorial coordinates the block adjustment method proposed by Stock (1981) was applied, using the Yale Position Catalogue (Hoffleit 1967) as reference source. The coefficients obtained show clearly the expected linear distortion term in the direction of the dispersion.

Since each object appears on at least two plate pairs, the internal rms errors of our final positions can readily be estimated. They turn out to be 0.3 arcseconds in both coordinates for data coming from a single plate pair.

VI. SPECTRAL TYPES

The spectra of each objet were classified along with the coordinate measurement. The assigned types are based on the appearance of both spectra. Having two spectra available, naturally the appearance of a subtle feature can more safely be distinguished from spurious plate effects. The types and luminosity classes are given in the MK-nomenclature, although none of the criteria recommended for the MK-classification was used. It is not pretended that the types and classes given are MK-types and classes. They should rather be understood as an attempt to predict the MK-classification from our low-dispersion spectra.

Only the major criteria used for the classification shall be described here. For A-stars we use the ratio K-line/Balmer lines. A-stars with obviously weak Balmer lines are classified as a w, or at times as A-supergiants. For the early F-stars we use the same criteria plus the structure of H_9. From F4 to G3 we use the ratio G-band/H-gamma. For later G-stars the absolute strength of H-delta is used. The CaI-line at 4227 Å appears at about G8, and its ratio to the G-band can be used up to the late K-stars. The appearance and strength of band heads is used for the classification of M-stars.

Luminosities can only be classified for late G-and for K-stars. This classification is based on the strength of a broad depression of the continuum around 4170 Å, and on the profile of an absorption band shortward of 3890 Å. Anomalies, such as strong CN, will lead to a wrong luminosity classification, as was shown by Clariá and Osborn (1976). Spectra with weak Ca II-lines and a weak G-band and no Balmer lines are classified as G pec, in accordance with the designation used by Stock and Wroblewski (1971). These are usually metal-weak late type stars.

The internal consistency of the spectral types is unexpectedly high. By comparing types coming from different plate pairs for the same objects we arrived at the conclusion that the final types given in our catalogue have an accuracy of about one subclass. The luminosity classes derived from different plate pairs coincide in about 75% of the cases.

VII. MAGNITUDES

The photographic densities of all spectra were estimated on an arbitary scale with the purpose of converting these into rough photographic magnitudes. These density estimates are calibrated with phographic magnitudes of whatever source was available. In most cases only the photometric data of the Yale Catalogue were available to us. Thus magnitudes fainter than the 11th magnitude in our catalogue are mostly based on extrapolations. On the average the accuray of our magnitude is estimated to be of the order of $0^m\!.3$.

VIII. COMPLETENESS OF THE SURVEY

The significance of the statistical analysis of any survey depends as much on the nature and accuracy of its data as it does on its completeness. External comparisons to check the latter are only possible if a similar survey is available. In the absence of such a comparison one can only enumerate those factors which in one way or another may affect the completeness of the survey. Among these the most important ones are:

1. *Apparent Magnitude.* Spectra which are too dense naturally cannot be measured. The maximum density which may be permitted depends strongly on the spectral type. The spectrum of a star of type O or early B of the apparent magnitude $10^m\!.0$ can just barely be measured on our plates. On the other hand, for a late type star of apparent magnitude $7^m\!.0$ the lines 21-24 can still be measured. At the other extreme, the spectra of A- and F-stars can be measured to a fainter limiting magnitude than G- or early K-stars because of the prominent Balmer series. Faint late K-stars can be measured again because the line 4227 of Ca I (No. 7) is very suitable for radial velocity measurements at our dispersion. At this point it should be mentioned that a special effort was made to measure very faint A-type stars since it was expected that these might be of particular interest. They are either main sequence or more luminous stars far away from the galactic plane, or they are subluminous stars at a short distance. On the whole, the survey should be complete to about the 12th apparent photographic magnitude. At the 13th magnitude most stars in our catalogue should be objects selected due to their special importance. On the basis of the apparent magnitude alone they would have been rejected. Also the limiting magnitude of completeness is not necessarily uniform over the entire surveyed area because the limiting magnitude of the different plates is not uniform, neither is their quality which also affects the density limit down to which spectra may be safely measured.

2. *Overlapping Spectra.* Overlaps are a problem inherent to objective prism techniques. The proportion of stars lost due to overlaps is expected to be independent

of the spectral type, but will depend on the apparent magnitude. A faint spectrum overlapped by a bright spectrum will normally be lost, but not necessarily so the bright spectrum. In view of the relatively low star density of the field surveyed we estimate that even at the faint limit of the survey the loss due to overlaps should be less than 10%.

3. *Missed Objects*. During the survey one can easily miss some spectra. However, since each field is covered by two plate pairs which are surveyed completely independently, it is very unlikely the same object has been overlooked on both pairs. Thus we believe that this contribution to incompleteness is insignificant.

IX. THE CATALOGUE

The final results are given in a catalogue which contains the following information:

Column 1: Running number.

Columns 2-4: Right ascension, equinox 1950. 0 (for epoch see Table 1.

Columns 5-7: Declination (for epoch see Table 1).

Column 8: Spectral type.

Column 9: Photographic magnitude.

Column 10: Radial velocity.

Column 11: Number of plate pairs.

Column 12: Total weight.

Column 13: Number in the Yale Catalogue.

Column 14: HD-number.

Column 15: An asterisk indicates that the star is listed by Stock and Wroblewski (1971).

The complete catalogue described above for the 10 053 stars from 12^h to 13^h and $-30°$ to $-35°$ has been published separately (Stock 1982) and is available from the author upon request.

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