The Galactic Rotation Effect in Late Type Stars.

By R. O. Redman, M.A.

1. *Introduction.*—From its shape and from general analogy with other celestial bodies it has long been suspected that the Milky Way system is in rotation. This more or less vague idea has in recent years been put on a firmer basis, and the conception of galactic rotation, associated chiefly with the names of Lindblad and Oort, is rapidly becoming one of the accepted theories of general astronomy. Oort's work,* where the theory is linked with observational evidence, and the strong support recently provided by Plaskett and Pearce,† have indeed helped, to a very great extent, our understanding of the motions of certain stars. With the radial velocities of objects of small peculiar motions, O and B stars, the interstellar calcium, *c*-stars and the Cepheid variables, and with stars of very great velocities, the galactic rotation theory has been very successful. These, however, are all peculiar or rare objects in space. When we turn to cooler stars difficulties appear.

Some of these difficulties are merely observational. As is now well known, the "galactic rotation" effect which is sought in radial velocities and in proper motions is a variation of the nature of a second harmonic in galactic longitude, and it also depends directly on the average distance from us of the objects whose movements are considered. Clearly it is easier to detect and estimate the size of this effect in the case of distant objects of high luminosity and small peculiar motion, than with nearer, fainter stars such as the late type giants whose peculiar velocities are large. Most of the suitable observational data at present available for the latter are found in proper motions. With these we have two additional difficulties. Systematic errors are likely to vary with right ascension and give a spurious galactic rotation effect on analysis, and any error in the precession constant will also affect all results. The total elimination of these two difficulties is by no means an easy task. Finally, radial velocities have not been determined for any appreciable number of these stars fainter than apparent magnitude 5·5—that is, for F—K giants at distances greater than 100 to 150 parsecs.

Besides these observational difficulties, there has been another point at which late type stars have not accorded so well with theory as those of greater luminosity and slower motions. From the term $r\mathrm{A} \sin 2(l-l_0)$ in radial velocities, or $[r\mathrm{A} \cos 2(l-l_0) + r\mathrm{B}]$ in proper motions, it is possible to deduce a value for l_0, the longitude of the centre of the galaxy. The B stars, interstellar calcium, etc., point to a centre at longitude 325° or 330°, agreeing with independent evidence, *e.g.* that from the globular clusters. Late type stars, on the other hand, give l_0 from 10° to 30° away. For instance, Schilt ‡ has derived three values from three different sources of proper motions and gets $l_0 = 351°$, 340°, and 337°. J. E. Merrill,§ using motions derived from the Yale

* *B.A.N.*, 120, 132, 133 (1927), 159 (1928).
† *M.N.*, **90**, 243, 1930.
‡ *A.J.*, **39**, 20, 1928.
§ *A.J.*, **39**, 90, 1929.

50°–55° catalogue, gets $l_0 = 348°$ and 0° from two solutions differing in detail. Oort from radial velocities for types A–G, gets $l_0 = 337°$ and 345° in two determinations.

Thus it appears very necessary that more information should be obtained concerning the relation of late type stars to the "galactic rotation" effect. The determination of radial velocities of such stars offers one line of attack. The method is slow but more reliable than those which use proper motions. It is desirable to consider objects as distant as is convenient, and it is best, if possible, to avoid stars of variable radial velocity. The K giants seem to form the most suitable class to consider; they are numerous and on the whole probably as little subject to variation as any stars in the sky, while those variables which do exist are likely to have a small range in radial velocity.

2. *Observations.*—Thus it was decided to observe K stars of apparent visual magnitude 7·0 to 7·5, within 10° of the galactic equator and north of declination − 10°. This last restriction was necessary since the work was to be done at the Dominion Astrophysical Observatory, Victoria, B.C. However, since these cover only right ascensions, 17^h to 8^h, more stars of the same magnitude were added from 8^h to 10^h and 15^h to 17^h, up to galactic latitude 45°. A few near the galactic pole were also observed. All the required data for position, magnitude, and type were taken from the H.D. catalogue. The list as originally drawn up contained an unknown number of dwarfs. Reference to proper motions showed these to be comparatively few; about half a dozen stars of large motion were struck off and also one or two binaries.

The object of these observations being essentially statistical, individual velocities with a high degree of accuracy were not required, and only one plate was taken of each star. The standard Cassegrain spectrograph on the 72-inch reflector at Victoria was used with one prism and a short focus camera. This arrangement gave spectra with a dispersion of about 90A per mm. at $H\gamma$, which is very small for a radial velocity programme. Observations were commenced in 1928 November and, as far as this paper goes, continued until 1929 December. 209 measurable plates were obtained in or near the galaxy and 36 near the galactic pole.

3. *Measurement.*—Tests showed that measurements of these spectra with the standard micrometer were more accurate, though slower, than those with the spectro-comparator. The micrometer was therefore used throughout. Spectra were taken of standard (giant) stars, and from these wave-lengths were obtained which were used throughout this work. About 25 lines were used in obtaining each velocity. At various times throughout the year spectra (26 in all) of other standard stars were photographed and measured to check the wave-lengths and the general method of procedure. The mean residual (with sign) from these 26 spectra was − 0·5 km./sec., while the probable error per plate was found to be ± 3·0 km./sec.

Dwarf stars did not give such good results. In their case the wave-lengths obtained, as mentioned above, appear to have a systematic error which makes the observed velocities 4 or 5 km./sec. more negative than they should be. The cause of this is obscure, the only reason which can be suggested is that the blends formed by the spectral lines alter a little with absolute magnitude. It must be remembered that with this small dispersion practically all observed lines are blends of two or more single lines of considerable strength. Since we are in general observing only giants, this systematic error is not of great importance.

A difficulty arises when one wishes to determine the probable errors of the velocities obtained. For the galactic stars only one plate of each was obtained, so that inter-comparisons were impossible. Three stars were selected at the galactic pole, H.D. 107469, 107854, and 116515, and respectively 8, 7, and 7 spectrograms were obtained. It was found later that the first of these is unfortunately a dwarf. However, from the inter-agreement of the plates, "probable errors" 2·9, 5·1, and 2·7 km./sec. were found. The mean of these is 3·6. Further, a camera used extensively on the same spectrograph gives spectra of about 3·5 times the dispersion used in this work, and for late type stars is considered to give velocities with a probable error of about 1 km./sec. In comparison, therefore, we would expect our spectra to give velocities with probable errors about 3·5 km./sec.

Since practically none of the stars investigated has had its velocity determined at other observatories, there is at present no external check on the results obtained here. The evidence given above, from standard stars, from the three stars at the galactic pole, and from comparison with spectra of another dispersion, goes to show that the average "probable error" is between 3 and 4 km./sec. For the present, then, 3·5 km./sec. is taken to be the average "probable error" per plate. The "probable error" of the "probable error" may be estimated as $\pm$ 0·4 km./sec. This last figure has not been obtained by any precise calculation; rather it is of the nature of a personal opinion.

4. *Elimination of Dwarfs.*—Since a few dwarfs with small transverse velocities may have escaped elimination by proper motion, and since their presence in this work is undesirable, an attempt was made to detect them by their spectra. Accordingly, a dozen standard dwarf spectra were taken and compared with those of standard giants. Inspection showed that many of the criteria for spectroscopic absolute magnitudes were of little or no value with the small dispersion employed. The intensity ratios of λ4215 to λ4250 and λ4455 to λ4462, and, to some extent, the relative intensities of $\lambda\lambda$4482, 4489, and 4495 were found useful. Only a small minority of the programme stars showed "dwarfish" features, and only two or three appeared to be dwarfs beyond doubt.

5. *Results and Discussion.*—Velocities were available for 225 stars, 210 in or near the galaxy and 15 near the galactic pole. In the calculations for solar motion, galactic rotation, etc., 24 stars were rejected, the criteria for rejection being: total annual proper motion $> 0''\cdot 1$, or observed velocity $>$ 100 km./sec., or "dwarfish" spectrum. It may be noted that four stars were found to have velocities greater than 100 km./sec. and, of these, two show moderate proper motion

($> 0''\cdot 1$ per year), and all four have giant spectra. Finally, there were left 188 galactic stars and 13 at the galactic pole. These were collected into 13 groups, the mean galactic co-ordinates and the mean velocity being found for each group, and with these values solutions were made for the solar motion and "galactic rotation." The method was the same as that used by Plaskett.* Eight different solutions were made and the results are tabulated below. V_0 is the solar velocity (in km./sec.) and L and B are the galactic co-ordinates (in degrees) of the solar apex. $\bar{r}A$ is the usual term associated with galactic rotation while l_0 is the longitude of the galactic centre. Assumed figures are in brackets, and the "probable error" is given with each calculated quantity.

Solution.	K.	V_0.	L.	B.	$\bar{r}A$.	l_0.	Average Group Residuals. Without Sign.	With Sign.
1	(0)	18·6±2·2	(22)	(20)	3·8±1·7	356±17	5·3	−5·3
2	−5·9±0·7	15·6±1·1	(22)	(20)	3·8±1·1	350±7	2·7	0·0
3	(0)	(20)	(22)	(20)	4·4±2·0	358±13	5·3	−5·1
4	−5·2±0·2	(20)	(22)	(20)	5·4±1·3	358±7	3·1	0·0
5	(0)	17·6±2·0	(22)	(20)	2·7±1·8	(330)	5·2	−5·2
6	(0)	21·7±1·5	50±4	20±14	5·4±1·4	18±7	3·5	−0·1
7	(0)	19·4±1·7	47±4·5	26±9	(0)	(0)	3·7	−1·5
8	(0)	(19·4)	(47)	(26)	3·4±1·2	22±10	3·3	−2·1

In the first five solutions a solar apex was assumed (at $\alpha = 271°$, $\delta = +28°$) in order to reduce the number of unknowns to a minimum. It was found that, unless a K term was included, values for V_0, $\bar{r}A$, and l_0 could not be found so as to furnish residuals not systematically negative. Since such a term has not hitherto appeared in the velocities of late type stars and, indeed, is no longer regarded as an indispensable feature of the motions of B stars, it seemed undesirable to consider it in this work. The alternative is either to admit a systematic error in the velocities or to reject the apex at (271°, + 28°). The latter seems to be the correct course to pursue in view of the absence of systematic error in the tests with standard giant stars (§3). Thus in solution (6) we find an apex at L = 50°, B = 20°, corresponding to $\alpha = 283°$, $\delta = +53°$. This is at some distance from our other assumed apex, but, despite the large "probable error" of B (due to the distribution of the stars in the sky), we find in proper motion work plenty of supporting evidence.

For instance, Dyson and Thackeray,† using the Greenwich catalogue, covering the zone 24°–32° N. declination, find apices as follows :—

K0 (1221 stars)	$\alpha = 273°$	$\delta = +51°$
K2 (392 ,,)	293°	+ 59°
K5 (229 ,,)	318°	+ 65°.

* *M.N.*, **88**, 395, 1928.

† *M.N.*, **79**, 201, 1919.

Strömberg * finds for K giants ($M \leqslant 4$) a solar apex at $\alpha = 282°$, $\delta = +43°$, with $V = 18{\cdot}3$ km./sec. In a recent analysis of proper motions,† Schilt and Miss Barney have remarked that there is strong evidence that the solar apex for giant G and K stars is at a higher declination than for dwarf stars belonging to the "main series." There is thus no reason to doubt the reality of our result. It is to be noted that in solution (7), where galactic rotation is not considered at all, the solar apex is at $L = 47°$, $B = 26°$, *i.e.* at $\alpha = 273°$, $\delta = +52°$, in almost exact agreement with the value given by Dyson and Thackeray for Ko stars. An important fact is that in this solution the residuals are not very much greater than in solution (6) and, further, do not show any great systematic trend. The addition of rotation terms to the solution (in (8)) does not make any appreciable improvement, but this is merely an indication that if both solar motion and galactic rotation are to be considered, they should be treated simultaneously as in (6).

Taking our true group velocities to be defined by the elements in solution (6), we find the average residual per star is 19·5 km./sec. This is practically the same as the average peculiar radial velocity computed from the mean velocity of each group. These K stars evidently have large peculiar motions and, owing to this, each of the observed group velocities is subject to an average "error" of 5 km./sec. We note that as far as mere numerical size is concerned, only two of the solutions above yield average residuals greater than this figure. Without more data our results are clearly subject to considerable uncertainty.

The quantity $\bar{r}A$, whenever included, has a value between 2·7 and 5·4 km./sec. Let us take the actual value to be 4 km./sec. Estimates of A have been made by Oort and by Plaskett. As far as present knowledge goes, the best value is 0·017 km./sec. per parsec, which would show $\bar{r}$ to be about 240 parsecs.

For comparison the mean parallax of these stars was found, using all available proper motions. The stars so used were not quite identical with those whose radial velocities had been determined, but were all on the original observing programme, and thus may be taken as homogeneous with those observed. Rejecting proper motions greater than $0''{\cdot}1$ per year, we have left 191 stars, and taking data from solution (6), viz. solar apex at $\alpha = 283°$, $\delta = +53°$, solar velocity 21·7 km./sec., and average peculiar velocity 19·5 km./sec, a mean parallax $0''{\cdot}0047$ was found. The distance corresponding to this is about 210 parsecs; it should be rather smaller than the true mean distance, so that the 240 parsecs obtained from galactic rotation may be considered to agree very satisfactorily.

The mean magnitude corresponding to the mean parallax is $+0^{m}{\cdot}6$, and corresponding to the mean distance from galactic rotation it is $+0^{m}{\cdot}35$. The true mean magnitude should be between these two values. This agrees with other evidence, for instance, that from the hypothetical parallaxes of binary stars.‡

* *Mt. Wilson Contributions*, **11**, 300, 1922.
† *A.J.*, **37**, 189, 1927.
‡ *M.N.*, **88**, 722, 1928; or Russell and Miss Moore, *A.J.*, **39**, 165, 1929.

Now although the $\bar{r}$A term is in comfortable agreement with other work, the case is otherwise with the value of l_0 which we obtain. An assumed value 330° (solution (5)) is clearly unsuitable. The other values range from 350° to 22°, our most satisfactory solution (6) giving 18°. We have seen earlier that a similar difficulty arose with the radial velocities of comparatively near late type stars, and that proper motion work also gave an l_0 (337° to 0°) differing considerably from the usually accepted value near 325° or 330°. Since all investigations with late type stars have given a similar result, it is most probable that the effect is real.

It seems probable that the phenomenon is intimately connected with star-streaming. The B stars, interstellar calcium, etc., which furnish us with the expected l_0 are not subject to star-streaming. On the other hand, most late type stars, and in particular the K stars investigated here, show directions of preferential motion. From a theoretical point of view * it is to be expected that the direction of stream motion would coincide with the direction of the galactic centre. The observed apices of star-streaming (removing solar motion) are usually taken to be near galactic longitudes 167° and 347° and practically on the galactic equator. This is not the direction of the usually accepted centre, but on the contrary it agrees much better with the l_0 from the " galactic rotation " effect in these cooler stars.

Schilt, who has been responsible for much of the proper motion investigations concerning galactic rotation, has recently published a paper † in which he considers the second harmonic term to be real (he takes it in right ascension rather than in galactic longitude), but rejects the rotation theory and suggests that the observations may be explained entirely by stream motion. The matter is not fully explained, but we are promised another paper on the subject. The still more recent work of Plaskett and Pearce, already mentioned, together with the evidence collected by Oort, makes the entire rejection of the rotation theory very difficult.

The complicated movements of the cooler stars form a more difficult problem than that furnished by the slow-moving B stars. A complete theoretical explanation is not yet available, but more observational data would no doubt help greatly our understanding of the matter, and the writer hopes to be able to continue the work outlined here. The method of using a small dispersion spectrograph and taking only one photograph of each star seems to be the best one to follow, since individual velocities are here of little interest. The chief danger lies in systematic rather than accidental errors. Until a fair number of independent observations from elsewhere are available the use of bright standard stars as checks seems to be the only possible safeguard.

6. *Summary.*—A description is given of the observation and analysis of the radial velocities of some two hundred seventh magnitude K stars situated near the galactic equator. A small dispersion spectro-

* Oort, *B.A.N.*, 159, 1928.
† *A.J.*, **39**, 143, 1929.

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graph was used and only one plate was taken of each star. The average "probable error" per plate is 3·5 km./sec. Solutions for the solar motion and "galactic rotation" confirm the high declination of the solar apex and high value for l_0, the longitude of the galactic centre, found with late type stars by other workers, who have used principally proper motions. The "$\bar{r}$A" term agrees satisfactorily with other estimates. The average peculiar radial velocity of these stars is about 20 km./sec. (four were found > 100 km./sec.) and there are definite signs of stream motion. It is significant that in all work on late type stars, the "l_0" agrees better with the apices of stream motion than with the usually accepted galactic centre.

I wish to thank the members of the observatory staff for the interest they have shown in this work; in particular the Director, J. S. Plaskett, who offered the original suggestion leading to the investigation, and has helped with advice on many points; also J. A. Pearce and C. S. Beals, who obtained some of the plates. I am also indebted to Professor Schlesinger who kindly furnished the proper motion data of the stars used.

A more complete account of this work will appear in the Publications of the Dominion Astrophysical Observatory.

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Periodic Variation in the Colours of the Two Equatorial Belts of Jupiter. (Second Paper.) By A. Stanley Williams.

The first paper on this subject was published in the *Monthly Notices*, **59**, 376, 1899. The observational data on which the conclusions depended consisted entirely of verbal descriptions of the colours of the two belts by a great many different observers. Some time previously Julius Schmidt of the Athens Observatory, the well-known observer and author of the great map of the moon, had used a numerical scale, ranging from 0 to 10, to express the degree of redness of certain stars; a similar scale of redness was adopted for indicating the redness of the belts, and the verbal descriptions of the colours by the various observers were converted into terms of this scale of redness. The colour of the great red spot, when at its maximum degree of redness, was assumed to be equal to 10 of this scale, 0 implying an entire absence of red colour.*

The observations of the various observers are usually remarkably accordant for the years when the belts were near a maximum or minimum of redness, notwithstanding the difficulty of converting verbal descriptions into terms of a numerical scale. This will be seen from the following results for 1879, when the S. equatorial belt (SEB.) was at

* No account was taken of bluish or greenish tints, although, strictly speaking, they should be considered to represent a negative or minus degree of redness.