Radial motion in the galactic system of globular clusters

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Summary. It is shown that the radial velocities of globular clusters close to the Galactic Centre direction are not consistent with a simple steady state model of the galactic halo. The result is unlikely to be altered significantly by subsequent improvements in distances, radial velocities or galactic models. The non-circular motion in this line of sight corresponds to an average of $\Pi = +60$ km/s.

1 Introduction

Ever since Shapley (1918) discovered the Sun’s non-central position in the Galaxy relative to the system of globular clusters, it appears to have been assumed that the system possesses some kind of steady state spheroidal configuration. In more recent times, it has been supposed that this configuration reflects an early state of the collapsing proto-galaxy. Studies of the radial velocities of globular clusters (e.g. Kinman 1959b) for example have generally revealed very large residual motions in the (galactic) radial direction and these have been interpreted as due to highly eccentric orbits originating in the collapse. In addition, the Sun has a rotation velocity relative to the globular cluster system of around 167 km/s. The fact that the Sun’s absolute rotation velocity exceeds this value is attributed to the intrinsic angular momentum of the globular cluster system.

A recent investigation (Clube & Watson 1978) of the radial velocities of certain RR Lyrae stars presumed to be distant galactic halo members has suggested this picture is not completely accurate. There are signs of strong systematic $\Pi$-motions and it is therefore of interest to enquire whether similar effects are present in the globular cluster system. In this paper, we examine the velocities of globular clusters observed in the general direction of the Galactic Centre. It is implicit a priori in our discussion that the system may possess some overall axially symmetric $\{\Pi(\bar{\omega}), \Theta(\bar{\omega})\}$ pattern in which $\Pi(\bar{\omega}) \neq 0$, and by concentrating our attention on those objects close to the Galactic Centre line of sight, we can expect to reduce the effect on $\Pi(\bar{\omega})$ of uncertainty in $\Theta(\bar{\omega})$ to a relatively low level.

2 The $\Pi(\bar{\omega})$ distribution

We list in Table 1 all the globular clusters (29) within $0^\circ < |l|, |b| < 20^\circ$ which have reasonably well-established distances $r$ (see, e.g. Harris 1976) and radial velocities (see, e.g.
Table 1. Globular clusters in the Galactic Centre region(1).

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<th>NGC</th>
<th>l (°)</th>
<th>b (°)</th>
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<th>(\rho_0)(3) (km/s)</th>
<th>(\rho)(5) (km/s)</th>
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Notes
(1) \(0^\circ < |l|, |b| < 20^\circ\).
(2) From Harris (1976).
(3) From Kukarkin (1974).
(4) From Hesser & Shawl (1977).
(5) Corrected to LSR.

Kukarkin (1974). The table gives their heliocentric radial velocities \(\rho_0\) and their velocities corrected to the local standard of rest, \(\rho\). In Fig. 1, we plot \(\rho\) against \(x = r \cos l \cos b\) for the objects in Table 1, and there is a clear pattern of generally negative velocities in front of the Galactic Centre followed by generally positive beyond the Galactic Centre. These features are just those found independently from the RR Lyrae stars mentioned above, and it is thus extremely probable that the \((\rho, x)\) distributions of both these halo representatives portray a real \(\Pi(\omega)\) distribution in the halo in which \(\Pi(\omega)\) differs significantly from zero.

The extent to which the \((\rho, x)\) distribution accurately represents the \(\Pi(\omega)\) distribution obviously depends on a precise rotation model and the peculiar velocity distribution. These factors are not known a priori and further deductions must be made with some care. Nevertheless, the globular cluster radial velocities and distances are inherently more accurate than those for faint RR Lyrae variables in the field and we can expect to establish the \(\Pi(\omega)\) pattern with somewhat greater precision.
Radial motions of globular clusters

Figure 1. Distribution of radial velocities $\rho$ with distance $x$ resolved in the direction of the Galactic Centre for 29 globular clusters with $0^\circ < |l|, |b| < 20^\circ$. Note the trend of negative velocities for clusters with $x < 7$ kpc to positive velocities for more distant objects.

First of all, however, the very fact of non-zero $\Pi(\hat{\omega})$ values is so surprising in relation to many preconceptions that it is of the greatest importance to check whether the general properties of Fig. 1 are imposed in some accidental way by faulty data or some kind of hidden correlation. In the next section, therefore, we consider the possibility of distance errors and velocity errors and the accidental effects of rotation depending on the correlation of $y = r \sin \ell \cos b$ and $z = r \sin b$ with $x$. In Section 4, we test how sensitive the general pattern of Fig. 1 is to variations in the presumed rotation of the globular cluster system.

3 Possible uncertainties in observational data

The distances ($r_H$ say) given by Harris (1976) were chosen as the most complete set making use of the most recent photometric data. Their intrinsic accuracy may be judged from a comparison with those ($r_R$ say) given, even more recently, by Rosino (1978) in an ‘independent’ investigation. It is found that for the 57 globular clusters in common $r_H$ and $r_R$ are generally in very close agreement and we note that individual uncertainties in $r$ probably do not exceed $\sim 10$ per cent. Harris’s distances thus appear to be very secure with a typical error perhaps of a few per cent. His distances do, however, differ to some degree from those given by Kukarkin (1974) in a slightly earlier study. Kukarkin’s distances correlate quite well with the original Kinman (1959a) data but the discrepancies with Harris are found to be largely attributable to the most recent photometric results ($> 1974$) which are not included in Kukarkin’s work. Notwithstanding these defects in Kukarkin’s data, we have plotted in Fig. 2 the ($\rho, x$) diagram for those 13 globular clusters to which he has attributed high weight distances. Although the properties of Fig. 2 are not as clear as those in Fig. 1, they are not in conflict since there is still a general positive correlation of $\rho$ with $x$. The correlation coefficient is $+0.37$ and even if it were correct to describe the trend by a simple linear regression, there is only a 10 per cent probability that such a value would arise by
chance from a true distribution with expectation values of $\rho = 0$. The probability that the same correlation should appear in both the globular clusters and the previously mentioned RR Lyraes is therefore on the order of a few per cent. So, even if improved distances had not recently become available, the deviation of the observed $(\rho, x)$ distribution from $\rho = 0$ is of such significance as to command attention.

The radial velocity data are substantially those given by Kinman (1959a) and depend on his mostly southern hemisphere observations and earlier work by Mayall (1946). Much of these data have been checked recently by Hesser et al. in interferometric searches for ionized hydrogen in globular clusters (e.g. Smith, Hesser & Shawl 1976; Hesser & Shawl 1977). Kinman's data turn out to be basically sound but there have been some indications of error in Mayall's velocities for very faint objects. Since some of these objects are in the Galactic Centre field, we have applied a rough correction of $+50\text{km/s}$ (Hesser & Shawl, private communication) to the assumed 10 suspect velocities and replotted the data. The exact values of any individual corrections have not been finally established as yet, and it would be premature to regard the revised plot as any more precise than Fig. 1, but even with this allowance for suspected uncertainties, the trend of $\rho$ with $x$ in Fig. 1 is essentially unaltered.

We conclude that it is very unlikely that the overall properties of Fig. 1 will be altered to a large extent by any subsequent improvements in either the individual distances or the radial velocities.

It is conceivable that the trend in $(\rho, x)$ that is attributed to $\Pi(\omega)$ could be caused fundamentally by $\Theta(\omega)$ and an accidental correlation of $y$ and (less plausibly) $z$ with $x$. To check whether it could be due to this effect, the distributions of $y$ and $z$ with $x$ are shown in Fig. 3, and it is evidently not likely that the positive trend of $\rho$ with $x$ in Fig. 1 can be considered due to any correlation of $y$ or $z$ with $x$. It is also conceivable that the trend has its origin in some correlation with metal abundance or age, but no significant effect has been found.
4 Possible uncertainties in galactic rotation model

In Fig. 4, the line labelled (i) is the running mean over eight points of the data given in Fig. 1. The error bar represents a range of 2σ/\sqrt{8} where σ is taken over all the individual residuals from the mean curve (but note that neighbouring points are strongly correlated). To test how sensitive the pattern in Fig. 1 is to variations in the galactic model, we have derived curves similar to (i) in Fig. 4 for a variety of galactic rotation and distance parameters by forming

\[ \rho' = \rho - \tilde{\omega}_0 \sin l \cos b \left( \frac{\Theta}{\tilde{\omega}} - \frac{\Theta_0}{\tilde{\omega}_0} \right) \]  

(i)

where \( \tilde{\omega}, \tilde{\omega}_0 \) are the radial distances of a globular cluster and the Sun in a galactocentric cylindrical coordinate system. \( \Theta, \Theta_0 \) are the corresponding circular velocities at \( \tilde{\omega} \) and \( \tilde{\omega}_0 \) respectively. By assuming either

\[ \Theta = \Theta_{00} \]  

(ii)

or

\[ \Theta = \frac{\tilde{\omega}}{\tilde{\omega}_0} \Theta_{00} \]  

(iii)

in which

\[ \Theta_{00} = \Theta_0 - V_0 \]

where \( V_0 \) is the mean retrograde motion of the globular cluster system with respect to the LSR, we can survey rotation models with constant velocity (ii) and no differential rotation.
Figure 4. Smoothed curves showing the distribution of \( \rho \) with \( x \): (i) when no correction is applied for the circular velocity of the globular cluster system (i.e. the data shown in Fig. 1), (ii) when the globular cluster system is assumed to be rotating with constant velocity and (iii) when the system is assumed to be rotating as a solid body. The arrows indicate the outer limits of the smoothing over eight points, and the error bar represents a range of \( 2\sigma/\sqrt{8} \) where \( \sigma \) is taken over all the individual residuals from the mean curve.

(iii). In practice, we have extended the survey to the following values:
\[
\tilde{\omega}_0 = 7, 8.5, 10 \text{ kpc},
\]
\[
V_0 = 130, 170, 210 \text{ km/s},
\]
\[
\Theta_0 = 250 \text{ km/s},
\]
but the form of the smoothed curves (\( \rho', x \)) like (i) in Fig. 4 is quite insensitive to variations in \( \tilde{\omega}_0 \) and \( V_0 \) (i.e. \(|\Delta \rho| < 20 \text{ km/s}\)) within this range and we therefore present further curves in Fig. 4 corresponding only to
\[
\tilde{\omega}_0 = 7 \text{ kpc} \text{ (see, e.g. Clube & Watson (1978) and references therein)}
\]
\[
V_0 = 170 \text{ km/s} \text{ (see, e.g. Kinman (1959b))}.
\]
The curves labelled (ii) and (iii) in Fig. 4 correspond to constant velocity and 'solid body' rotations respectively in the halo, and it is clear once again that the general form of (i) is really quite robust whatever plausible estimates of the unknown properties of the Galaxy are used. Some confidence may therefore be placed in the general properties of (i), (ii) and (iii) in Fig. 4.

5 General properties of the (\( \rho, x \)) distribution

If a minimum requirement of any interpretation of Fig. 4 is symmetry in the velocity field on either side of the Galactic Centre, the fact that we observe negative \( \rho \) for small \( x \) changing to positive \( \rho \) for large \( x \) suggests a general consistency with positive \( \Pi \) originating from a
centre at about $x \sim 7$ kpc where $\rho$ changes most rapidly from negative to positive values. Obviously the choice of $x \sim 7$ cannot be settled by this argument, but the independent evidence for the distance to the Galactic Centre obtained from: (1) all the globular cluster data ($\bar{\omega}_0 \geq 7$ kpc: Harris 1976) and (2) RR Lyrae stars ($\bar{\omega}_0 = 7$: Clube & Watson 1978), confirms this value, and suggests the interpretation of Fig. 4, however speculative at first sight, is probably not incorrect.

To estimate $\Pi_0$ for the local standard of rest and $\bar{\omega}_0 (= x_0)$ from Fig. 4, we raise the $x$ axis until the negative area under the curve between $x = 2.5$ kpc and $x = x_0$ is equal to the positive area under the curve between $x = x_0$ and $x = 2x_0 - 2.5$. The choice of $x = 2.5$ kpc is arbitrary but is the minimum necessary to include all the points on the nearside of the Galactic Centre and maximize the selection from the far side. By this procedure we obtain $x_0 = \bar{\omega}_0 = 6.7$ kpc to a very high degree of precision ($\sim \pm 0.25$ kpc se) and $\Pi_0 = +10$ km/s with much less certainty ($\sim \pm 10$ km/s se). Nearby clusters ($x < 3$) outside the area discussed tend towards $\rho \sim 0$, and the inclusion of these would undoubtedly increase our estimate of $\Pi_0$. The value of $\Pi_0$ is thus tolerably consistent with earlier estimates of $\sim 40$ km/s from independent data (Clube 1978). The agreement between the ‘kinematic’ estimate of $\bar{\omega}_0$ and the above ‘geometrical’ values adds weight to our earlier speculation that the globular cluster distances are now consistent with the distance scale given by nearby halo RR Lyraes ($M_V \sim 0.9$, $\Delta S \sim 7$) in spite of the cluster distances being calibrated against brighter absolute magnitude of RR Lyraes ($M_V \sim 0.6$). This may be attributed to a possible general correlation between $M_V$ and $\Delta S$ of the kind found by Clube & Dawe (1978). A very similar correlation appears in globular clusters containing RR Lyraes and which have been fitted to a common main sequence (Liller 1978). However, it must be noted that no physical reason for this correlation is yet known.

To obtain finally a best estimate of the $\Pi(\bar{\omega})$ distribution from the globular cluster data, we reflect the points of Fig. 4 (ii) through $\rho = 40$, $x = 7$ and form the running mean as before. The resultant smooth curve is displayed in Fig. 5. Although it is not possible to be certain of the halo value of $\Pi(\bar{\omega}_0)$, there is approximate agreement between this running

![Figure 5](https://example.com/figure5.png)

**Figure 5.** ($\rho, x$) distribution for the globular clusters from Fig. 4(ii) reflected about $\rho = 40$ km/s, $x = 7$ kpc and smoothed by eye to give an estimate of the galactic $\Pi(\bar{\omega})$ distribution. The ($\rho, x$) distribution of RR Lyraes (from Clube & Watson 1978) similarly reflected is also shown.
mean and the previously estimated behaviour of Drift II (see Clube 1978) and halo RR Lyraes (Clube & Watson 1978).

6 Conclusions

Any simple interpretation of globular cluster radial velocities along the lines of this investigation will produce a $\Pi(\tilde{\omega})$ pattern in the halo similar to that of Fig. 5. This is therefore a property of the galactic halo not previously suspected and which must be incorporated in any viable theory. Strictly speaking, the derived $\Pi(\tilde{\omega})$ distribution applies only to a limited galactocentric sector taking in the Sun. Although axial symmetry has been adopted as a simple initial assumption, it cannot really be established from the globular cluster data, and it is possible in principle that the $\{\Pi, \Theta\}$ distribution also includes an azimuthal dependence. The justification for including azimuthal terms or otherwise depends entirely on the physical circumstances giving rise to the observed radial motions. Whatever these circumstances are, it is evident that the immediate observed structure of the halo is not a simple steady state and cannot survive. Whether the structure corresponds to a strictly periodic departure from an equilibrium state perhaps induced by the rotation of a massive bar-like object in the centre of the Galaxy, or is more symptomatic of a recent violent event in the centre of the kind discussed by Clube (1978) remains to be settled. The very large size of the instantaneous $\Pi$-motions ($\sim 60 \text{ km/s}$) does, however, introduce severe difficulties for schemes involving a massive bar.

Acknowledgment

We thank Mrs M. Fretwell for preparing the diagrams in this paper.

References