The Proper Motion of NGC 6522 in Baade’s Window

Donald M. Terndrup, Piotr Popowski, and Andrew Gould

Department of Astronomy, The Ohio State University,
174 W. 18th Ave., Columbus, Ohio 43210
Electronic mail: (terndrup,popowski,gould)@astronomy.ohio-state.edu

R. Michael Rich

Department of Astronomy, Pupin Laboratories, Columbia University, 538 West 120th Street, New York, New York 10027
Electronic mail: rmr@astro.columbia.edu

Elaine M. Sadler

School of Physics, University of Sydney, NSW 2006, Australia
Electronic mail: ems@physics.usyd.edu.au

Received ________________; accepted ________________

1 Based in part on data obtained at the Anglo-Australian Observatory and at the Cerro Tololo Inter-American Observatory, NOAO, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.

2 Alfred P. Sloan Fellow.
We have detected seven stars with a common proper motion which are located within 2.5 of the globular cluster NGC 6522 in the Baade’s Window field of the Galactic bulge. We argue that these stars are members of the cluster, and derive a weighted mean proper motion and heliocentric radial velocity of $\bar{\mu}_l = 1.4 \pm 0.2$ mas yr$^{-1}$, $\bar{\mu}_b = -6.2 \pm 0.2$ mas yr$^{-1}$, $\bar{v} = -28.5 \pm 6.5$ km s$^{-1}$. We rederive the distance to NGC 6522 $(0.91 \pm 0.04 R_0$, where $R_0$ is the Galactocentric distance) and metallicity ([Fe/H] $= -1.28 \pm 0.12$), making use of recent revisions in the foreground extinction toward the cluster ($A_V = 1.42 \pm 0.05$). We find the spatial velocity of the cluster and conclude that the cluster stays close to the Galactic center, and may have experienced significant bulge/disk shocking during its lifetime.

Subject headings: astrometry – Galaxy: abundances – globular clusters: individual (NGC 6522) – stars: kinematics
1. Introduction

Three-dimensional space motions of individual stars and stellar systems throughout the Galaxy are an important probe of the Milky Way's gravitational potential and of the kinematics of different populations within it. Most of what we know, for example, about the disk and halo of the Galaxy has come from studies of the radial velocities and proper motions of stars in the local volume of space near the Sun. In recent years, this has been steadily extended to samples throughout the Galaxy, particularly for globular clusters (Cudworth & Hanson 1993; Dauphole et al. 1996) and the Large Magellanic Cloud and other Galactic satellites (e.g., Jones et al. 1994; Schweitzer & Cudworth 1996; Ibata et al. 1997).

A potentially important sample for in situ studies of the Galactic bulge is the proper motion survey of Spaenhauer et al. (1992 - hereafter SJW). This survey contains relative proper motions of 427 stars in the Baade's Window field of the nuclear bulge at $(\ell, b) = (1.0^\circ, -3.9^\circ)$, which samples stellar orbits relatively close to the Galactic center (minimum line of sight distance $\approx 550$ pc). The proper motions presented by SJW are with respect to the mean motion of the entire sample (i.e., they set $\bar{\mu}_\ell \equiv 0, \bar{\mu}_b \equiv 0$), since no extragalactic reference frame is available.

We have been conducting an extensive photometric and spectroscopic followup of the SJW survey. In our first paper (Terndrup et al. 1995), we presented methods of analysis and demonstrated that the sample contains a considerable number of stars located in front of the bulge. In the second paper (Sadler et al. 1996), we derived individual metallicities and distances to the SJW stars. In preparing for a full analysis of the space motions in Baade's Window (Rich et al. 1998), we have discovered that a number of stars with proper motions in Baade's Window are likely to be members of the globular cluster NGC 6522. In §2 we describe the procedure by which the stars are identified as cluster members, measure
the proper motion of the cluster relative to the mean proper motion of the SJW sample, and estimate the cluster's radial velocity. In §3, we analyze the cluster color-magnitude diagram (CMD) and derive estimates for the cluster metallicity and distance. In §4, we estimate the space motion of the cluster and discuss its orbit.

2. Identification of Cluster Members

We begin by selecting the 406 stars that have radial velocities (Terndrup et al. 1995) out of the 427 stars in the SJW survey. We first demonstrate that members of NGC 6522 are present in the SJW survey by noting that there are several stars with a common proper motion which have radial velocities near the value previously determined for the cluster.

The radial velocity of NGC 6522 has been reported several times in the literature. Rich (1990) obtained the radial velocity of two stars near the cluster center from spectra of resolution 1.9 Å; the average heliocentric velocity of these was \( v = -25.6 \pm 1.5 \text{ km s}^{-1} \), identical to the value of \( -25 \pm 16 \text{ km s}^{-1} \) derived from Fabry-Perot observations at H\( \alpha \) by Smith et al. (1976). Averaging a variety of observations, including the Smith et al. (1976) value, Webbink (1981) obtained \( v = +8 \pm 16 \text{ km s}^{-1} \). As Webbink himself noted, however, the velocities he included in the average for NGC 6522 formed a bimodal distribution; it is therefore likely that several bulge stars were included in the computation. In his compilation of globular cluster velocities, Zinn (1983) repeats the Webbink (1981) value. Pryor & Meylan (1993) quote the radial velocity as \( -10.4 \pm 1.5 \text{ km s}^{-1} \) from an apparently unpublished paper. Recently, Rutledge et al. (1997) obtained Ca II spectra of 18 stars near the cluster, and derived \( v = -18.3 \pm 9.3 \text{ km s}^{-1} \), where the uncertainty is the standard error of the mean.

\( ^3 \)SJW tabulated 429 stars, but listed the stars Arp 3-144 and 4-027 twice.
In the upper panel of Figure 1, we display the proper motion vector point diagram for the complete SJW survey, while in the lower panel we show those stars located within 2.5 of the cluster center with radial velocities statistically consistent at the 1σ level with the Smith et al. (1976) value of \(-25 \pm 16\) km s\(^{-1}\). The error bars in the lower left hand corner of Figure 1 show the mean error in proper motion for the stars in the sample. In the lower panel, one clumping of points is present at \((\mu_\ell, \mu_\theta) \sim (1.5, -6)\) mas yr\(^{-1}\). As we will show, this is the most likely proper motion of the cluster because stars near this clump lie on the giant branch for NGC 6522 and have absorption line strengths unlike most of the stars in the bulge; other possible clumps of stars in Figure 1 do not yield this a posteriori consistency with the cluster CMD and metallicity.

To identify cluster members, we employ an iterative scheme which searches for stars in the SJW sample that are simultaneously within 1.5σ of the mean cluster motion \((\bar{\mu}_\ell, \bar{\mu}_\theta, \bar{\mu}_c)\) in each proper motion component and in radial velocity. For example, for heliocentric radial velocity component, we demand that

\[ |v_i - \bar{v}_c| \leq 1.5\sigma_i, \tag{1} \]

where \(v_i\) is the velocity of an individual star, \(\bar{v}_c\) is the mean velocity of cluster members,

\[ \sigma_i^2 \equiv \epsilon_i^2 + \sigma_c^2(v), \tag{2} \]

\(\epsilon_i\) is the measurement error, and \(\sigma_c(v)\) is the estimated scatter due to the internal velocity dispersion of the cluster. Similar expressions are used for \(\mu_\ell\) and \(\mu_\theta\). We adopt \(\sigma_c(v) = 6.7\) km s\(^{-1}\) (Pryor & Meylan 1993). For a distance to NGC 6522 of 7.1 kpc (below), this corresponds to \(\sigma_c(\mu_\ell) = \sigma_c(\mu_\theta) = 0.20\) mas yr\(^{-1}\), which we adopt for the dispersion in each component of the proper motion. (The results of this procedure are not very sensitive to the choice of \(\sigma_c\) because \(\epsilon_i \geq \sigma_c\) for most of the sample.)

We began the iteration with a few stars near the clump in the lower panel of Figure 1. Then at each step, the list of stars near the mean cluster motion was used to recompute the
weighted means \( \langle \mu_{\ell,c}, \mu_{b,c}, \bar{v}_c \rangle \), with weights \( 1/\sigma_i^2 \) in each component. This process quickly converged on seven stars, which are listed in Table 1. The star names in the first column are from Arp (1965). Columns 2-7 show the radial velocity and photometry (Terndrup et al. 1995). The next four columns contain the proper motion and errors from SJW, where the units are mas yr\(^{-1}\). The last column shows the angular distance of each star in arcmin from the center of NGC 6522.

At this point we examined the errors in proper motion and radial velocity to confirm that they were estimated correctly, for if the selected stars truly are members of the cluster the scatter in projected motion should be almost entirely due to observational error. Via a \( \chi^2 \) test, we determined that the scatter in proper motions about the mean value is consistent with the errors, but the errors for the radial velocities were too large by a factor of \( \sim 1.7 \). The reason for this is not completely clear. As discussed by Terndrup et al. (1995), the radial velocity errors were estimated from the width of the peak in the cross-correlation between the bulge stars and a set of radial velocity templates; intercomparisons between multiple measures allowed them to confirm that the error estimates were, in general, approximately right. The possible cluster members, however, happen to be among the most metal-weak of the stars in the SJW sample (below), which could have led to an overestimate of the error because of the resulting mismatch between these stars and the velocity standards. An examination of the estimated errors as a function of metallicity (Sadler et al. 1996) reveals that this explanation is plausible: the mean estimated error in radial velocity for stars with [Fe/H] < -0.7 is 25 km s\(^{-1}\), compared to 15 km s\(^{-1}\) for stars with [Fe/H] > -0.7.

We then scaled the radial velocity errors downward by a factor of 1.7 (but not below a reasonable minimum value of 7 km s\(^{-1}\)) and repeated the iterations, obtaining the same list of candidate members of NGC 6522. The weighted mean cluster motion and standard
errors of the mean from this sample are
\[ \overline{\mu}_{c} = +1.2 \pm 0.2 \text{ mas yr}^{-1}, \]
\[ \overline{\mu}_{b,c} = -6.0 \pm 0.2 \text{ mas yr}^{-1}, \]
\[ \overline{\sigma}_{c} = -28.5 \pm 6.5 \text{ km s}^{-1}. \]

The radial velocity we derive is in statistical agreement with the value of \(-18.3 \pm 9.3 \text{ km s}^{-1}\) from spectra of 18 stars near the cluster reported by Rutledge et al. (1997).

Finally, in order to explore the sensitivity of our selection method, we compute membership probabilities for the SJW stars with radial velocities assuming a Gaussian distribution for the cluster and field (mostly the bulge) and taking into account the errors in the individual measurements (cf. Dinescu et al. 1996). We write the mean apparent motion of the field as \(\{\overline{\mu}_{f,i}, \overline{\mu}_{b,f,i}, \overline{\sigma}_{f}\}\) and the dispersion as \(\{\sigma_{f} (\mu_{c}), \sigma_{f} (\mu_{b}), \sigma_{f} (v)\}\). Denoting with the subscript \(c\) the equivalent quantities for the cluster, determined above, we define the membership probability for star \(i\) as
\[ P_{i} = \frac{\rho_{i,c}}{\rho_{i,c} + \rho_{i,f}}, \]
where the densities \(\rho_{i,c}\) and \(\rho_{i,f}\) of cluster and field stars are represented as the Gaussian distributions
\[ \rho_{i,c} = \frac{N_{c}}{(2\pi)^{3/2}\sigma_{i}(\mu_{c})\sigma_{i}(\mu_{b})\sigma_{i}(v)} \exp \left[ -\frac{(\mu_{c,i} - \overline{\mu}_{c})^2}{2\sigma_{c}^2(\mu_{c})} - \frac{(\mu_{b,i} - \overline{\mu}_{b,c})^2}{2\sigma_{c}^2(\mu_{b})} - \frac{(v_{i} - \overline{\sigma}_{c})^2}{2\sigma_{c}^2(v)} \right], \]
\[ \rho_{i,f} = \frac{N_{f}}{(2\pi)^{3/2}\sigma_{f}(\mu_{c})\sigma_{f}(\mu_{b})\sigma_{f}(v)} \exp \left[ -\frac{(\mu_{f,i} - \overline{\mu}_{f})^2}{2\sigma_{f}^2(\mu_{c})} - \frac{(\mu_{b,i} - \overline{\mu}_{b,f})^2}{2\sigma_{f}^2(\mu_{b})} - \frac{(v_{i} - \overline{\sigma}_{f})^2}{2\sigma_{f}^2(v)} \right]. \]

Note that in the expression for the cluster density function we combined the errors of the individual stars and the adopted cluster dispersion as in equation (2). The values for the field were derived from the SJW stars with velocities excluding the seven stars in Table 1, and were \(\overline{\mu}_{f} = 0.04 \text{ mas yr}^{-1}\), \(\sigma_{f} (\mu_{c}) = 3.1 \text{ mas yr}^{-1}\), \(\overline{\mu}_{b,f} = 0.18 \text{ mas yr}^{-1}\), \(\sigma_{f} (\mu_{b}) = 2.7 \text{ mas yr}^{-1}\), \(\overline{\sigma}_{f} = -2.1 \text{ km s}^{-1}\), \(\sigma_{f} (v) = 105 \text{ km s}^{-1}\). As opposed to the cluster
members, the field stars' dispersions are dominated by the intrinsic velocity dispersions and not observational errors. Figure 2 displays the membership probabilities, expressed as percentages, against (top panel) the distance from the center of NGC 6522 and (bottom panel) the $V$ magnitude. The stars in Table 1 are those seven stars with the highest membership probabilities; all seven have $P \geq 85\%$. There are only three other stars with $P \geq 10\%$, and most of the sample has $P$ very nearly zero. (The SJW sample contains almost no stars within 1′ of the cluster because this region was deliberately avoided in their survey.)

3. The distance to NGC 6522

To support our claim that we have found members of NGC 6522 in the SJW survey, we now examine photometry and line-strength indices (Terndrup et al. 1995) for the stars in Table 1. We also derive the distance to NGC 6522, needed for the conversion of proper motion into a space velocity, from its CMD and by direct comparison of its HB magnitude to that of RR Lyrae stars in Baade's Window. In this process, we obtain a photometric metallicity estimate for comparison to recent results from spectroscopy.

The distance to NGC 6522 is not known accurately: although there are several RR Lyrae stars near the cluster, it is difficult to determine which are members and which are in the bulge (Blanco 1984; Walker & Mack 1986; Walker & Terndrup 1991; Carney et al. 1995). Consequently the only distance estimates have come from analysis of the cluster's CMD, and these are sensitive to the assumed metallicity of and extinction towards the cluster. For example, Terndrup & Walker (1994) derived $[\text{Fe}/\text{H}] = -1.6 \pm 0.2$ and $(m - M)_0 = 14.8 \pm 0.3$ ($d = 9.1^{+1.4}_{-1.2}$ kpc) from comparison of the cluster CMD to the giant branches of globular clusters in Da Costa & Armandroff (1990). This derivation was for $E(V - I) = 0.65 \pm 0.07$, and the Da Costa & Armandroff (1990) sequences were tied to the Lee et al. (1990)
calibration of RR Lyrae absolute magnitudes of $M_V(RR) = 0.82 + 0.17[\text{Fe/H}]$. The metallicity that Terndrup & Walker (1994) derived was in agreement within the errors to the Zinn & West (1984) value $[\text{Fe/H}] = -1.44$ from integrated colors.

Nearly simultaneously with Terndrup & Walker (1994), Barbuy et al. (1994) presented their own CMD of the cluster and derived extinction values and metallicity by comparison to the CMD of NGC 6752, which has $[\text{Fe/H}] = -1.54$ (DaCosta & Armandroff 1990 and references therein). They find $E(B - V) = 0.55 \pm 0.05$, which corresponds to $E(V - I) = 0.68 \pm 0.06$ (i.e., close to the Terndrup & Walker 1994 value) and a distance modulus of $(m - M)_o = 13.96$ ($d = 6.2$ kpc). They assume a horizontal branch luminosity of $M_V = +0.6$ and obtain a very approximate metallicity estimate of $[\text{Fe/H}] \approx -1.0$. Together, these two estimates imply that they were using a horizontal branch luminosity scale which is slightly (0.05 mag) more luminous than the Lee et al. (1990) scale employed by Terndrup & Walker (1994). Note, however, that the difference in horizontal branch luminosity scale is far too small to explain the 0.8 mag difference in the distance determinations; the largest effect comes from the choice of horizontal branch magnitudes on the CMD in the two analyses.

To derive the metallicity of the cluster, we reanalyze the photometry of Terndrup & Walker (1994) using the method outlined by Sarajedini (1994). Their method uses polynomial fits to the DeCosta & Armandroff (1990) giant branch sequences to measure simultaneously the metallicity of and extinction toward a cluster from color-magnitude diagrams in $V, V - I$. In using this method, we make two changes to reflect recent developments. First, we use the Stanek (1996) reddening map for Baade’s Window, which allows us to correct the photometry of the cluster (and of the probable cluster members in Table 1) for the considerable variation in extinction with position. Second, we adopt the Carney et al. (1992) calibration of the RR Lyrae luminosity ($M_V = 1.01 + 0.16[\text{Fe/H}]$)
instead of the Lee et al. (1990) scale implicit in the Sarajedini (1994) approach; since the metallicity slope is almost the same for both calibrations, this has the effect of reducing the derived distance by 0.2 mag. We adopt the Carney et al. (1992) scale so that our distance for NGC 6522 is on the same system as Galactic center distance from RR Lyrae stars in Baade’s Window (Carney et al. 1995). This way the relative distance between the cluster and the Galactic center can be found independent of the zero point in the calibration of RR Lyrae luminosity.

In employing the Stanek (1996) map, we first add an offset of $-0.10$ to $A_V$ (i.e., the reddening is less than in Stanek’s map) as discussed by Gould et al. (1998) and confirmed by Alcock et al. (1998a). Next, we interpolate across a region of radius 2′ around NGC 6522 which is not included in the map. An inspection of photographs of Baade’s Window (e.g., Blanco 1984) shows that, at least near the cluster, the gradient in extinction is primarily north-south with the extinction lower to the north of the cluster. In Figure 3, we show the Stanek redenings (with the corrected zero point) for the stars in the SJW survey as a function of the declination difference between each star and the cluster center (positive values indicate stars north of the cluster center). The straight line shows a linear fit to the redenings; the rms scatter about this line is 0.06 in $A_V$. From this plot and the Stanek (1996) relation $A_V = 2.49E(V - I)$, we conclude that the total and selective extinctions towards the center of the cluster are $A_V = 1.42 \pm 0.05$, and $E(V - I) = 0.57 \pm 0.02$.

In Figure 4 we display (left panel) a CMD in $V, V - I$ for stars within 1.5 of NGC 6522 (small points) along with the photometry for the cluster members in Table 1 (large filled points). The right panel shows the photometry for stars farther than 2′5 from the cluster center. In this figure, the photometry is from the sources listed in Terndrup & Walker (1994) and Terndrup et al. (1995); all the colors and magnitudes have been corrected to the reddening adopted for the cluster center using the linear fit to the reddening with position.
in Figure 3. The curved line is a quadratic fit to giant-branch stars on the left panel of Figure 4 (not only the possible proper motion members) using a 3σ rejection criterion. Note that, in support of our selection method, the possible cluster members are near the cluster’s giant branch and well away from the majority of bulge stars. (The scatter about mean giant branch is significantly worse without the use of the Stanek (1996) reddening map.)

Returning to the distance determination for the cluster, we note that the level of the horizontal branch at a representative color for RR Lyrae stars \((B - V = 0.80\), at the reddening to the cluster) is \(V = 16.50 \pm 0.15\). This is consistent with the HB level on the much better CMD of NGC 6522 from HST in Sosin et al. (1997); interpolating from their CMD, we find \(V_{HB} = 16.52 \pm 0.07\). Using this value for \(V_{HB}\), we apply the Sarajedini (1994) method and derive \([\text{Fe/H}] = -1.28 \pm 0.12\). The metallicity we derive agrees with the Rutledge et al. (1997) value \([\text{Fe/H}] = -1.21 \pm 0.04\), derived from infrared Ca II-triplet measures transformed to the high-resolution abundance scale of Carretta & Gratton (1997). The method simultaneously returns the estimate of the cluster reddening of \(E(V - I) = 0.58 \pm 0.03\) in excellent agreement with the value \(E(V - I) = 0.57 \pm 0.02\) derived from the corrected Stanek (1996) extinction map, and an estimate of the cluster distance modulus of 14.3 ± 0.1 on the Carney et al. scale (see also below).

In Figure 5, we plot the Lick Mg2 indices as a function of color for the Baade’s Window sample (Terndrup et al. 1995). The filled points with error bars are for the stars in Table 1. With the possible exception of Arp 2-069, which has a value of Mg2 about 1.8σ above that of the others, all the possible cluster members have low Mg2 indices at a given color, unlike those for the bulge stars in the SJW sample. Since the calibration of the Lick indices with metallicity is uncertain for stars of low metallicity (Sadler et al. 1996), we do not attempt to measure the abundance of NGC 6522 from these Mg2 indices – we simply note that the probable members are among the lowest-metallicity stars in Baade’s Window, consistent
with both the photometric and spectroscopic determinations of the abundance of NGC 6522.

A direct calculation of the relative distance between the cluster and the Galactic center is as follows: an analysis of the magnitudes of RR Lyrae stars in Baade's Window shows that the dereddened visual magnitude of the horizontal branch at typical colors of RR Lyrae stars is \( V_{0,\text{BW}} = 15.33 \pm 0.03 \) (Alcock et al. 1998b); there is an additional error from the uncertainty in extinction which does not enter here because we are comparing the cluster HB and the bulge HB in the same field. Taking the dependence of the horizontal branch level as
\[
M_{V,\text{HB}} = a + b[\text{Fe}/\text{H}],
\]
and using the definition of distance modulus we write the difference in distance moduli between the cluster and the Galactic center as
\[
\Delta c,\text{BW} = (V_{\text{HB},c} - A_V - M_{V,c}) - (V_{0,\text{BW}} - M_{V,\text{BW}}),
\]
where the subscript \( c \) refers to the cluster and the subscript \( \text{BW} \) to the RR Lyrae stars in Baade's Window. With the adopted reddening to NGC 6522, this becomes
\[
\Delta c,\text{BW} = (-0.23 \pm 0.08) + b([\text{Fe}/\text{H}]_{\text{BW}} - [\text{Fe}/\text{H}]_{c}).
\]
We found \([\text{Fe}/\text{H}]_{c} = -1.28 \pm 0.12 \) (above), and we adopt \([\text{Fe}/\text{H}]_{\text{BW}} = -1.1 \) (Walker & Terndrup 1991). Setting \( b = 0.16 \pm 0.10 \), we have
\[
\Delta c,\text{BW} = -0.20 \pm 0.08.
\]
For a distance to the Galactic center of 7.8 kpc, the cluster is therefore at a distance of \( 7.1 \pm 0.3 \) kpc. We will adopt this distance in the analysis that follows.
4. Space Motion

Because the SJW survey was not tied to an extragalactic reference frame, some care is required to transform this measurement into an estimate of the cluster's space motion. We begin by writing the observed vector proper motion \( \boldsymbol{\mu}_{\text{obs}} \) as

\[
\boldsymbol{\mu}_{\text{obs}} = \frac{\mathbf{v}_{\text{cl},\perp} - \mathbf{v}_{\odot,\perp}}{d_{\text{cl}}} - \frac{\mathbf{v}_{\text{f},\perp} - \mathbf{v}_{\odot,\perp}}{d_{\text{f}}} - \Delta \mathbf{\mu},
\]

where \( d_{\text{cl}} \) and \( \mathbf{v}_{\text{cl},\perp} \) are the distance to the cluster and its velocity transverse to the line of sight, \( d_{\text{f}} \) and \( \mathbf{v}_{\text{f},\perp} \) are the mean distance and transverse velocity of bulge field stars in Baade's Window, \( \mathbf{v}_{\odot,\perp} \) is the velocity of the Sun transverse to the line of sight, and \( \Delta \mathbf{\mu} \) is a correction to be discussed below. (Note that 1 mas yr\(^{-1} \) = 4.74 km s\(^{-1} \) kpc\(^{-1} \).) Next, we solve for \( \mathbf{v}_{\text{cl},\perp} \) and write the result in a way that allows easy identification of the role of various uncertainties,

\[
\mathbf{v}_{\text{cl},\perp} = d_{\text{cl}} \left( \boldsymbol{\mu}_{\text{obs}} + \Delta \mathbf{\mu} + \frac{\mathbf{v}_{\text{f},\perp}}{d_{\text{f}}} \right) + \mathbf{v}_{\odot,\perp} \left( 1 - \frac{d_{\text{cl}}}{d_{\text{f}}} \right). \tag{12}
\]

We now estimate \( \Delta \mathbf{\mu} \), the mean proper motion of bulge stars relative to the proper-motion frame of the SJW stars. There are two distinct sources of contamination that lead to an offset: foreground disk stars and the cluster stars themselves. To estimate the offset due to foreground disk stars, we focus on the subsample of 310 stars (out of a total of 427) with spectroscopic distance estimates from Sadler et al. (1996). We compare the 241 stars with distances > 4 kpc with the full subsample of 310 stars and find an offset \( (\Delta \mu_t, \Delta \mu_b) = (0.16, -0.05) \) mas yr\(^{-1} \). We assume that this offset is representative of all 427 stars. The full SJW sample contains \( \sim 330 \) stars at distances > 4 kpc, of which \( \sim 7 \) are cluster members. The offset due to cluster stars is therefore \( 7/330 \sim 2\% \) of the value given in equation (3), or \( (\Delta \mu_t, \Delta \mu_b) = (0.02, -0.12) \) mas yr\(^{-1} \). Within the accuracy of our determinations, the combined offset from these two sources of bias is therefore

\[
(\Delta \mu_t, \Delta \mu_b) = (0.2, -0.2) \text{ mas yr}^{-1}. \tag{13}
\]
The distance to the Galactic center is uncertain (e.g. Reid 1993), but for present purposes, we treat it as being fixed at the distance given by the Carney et al. (1992, 1995) scale, 7.8 kpc, and scale all results to this value. Recall that we have also estimated the distance to the cluster on this scale. Since Baade's Window is very close to the minor axis of the bulge (at $\ell = +1^\circ$), a fair sample of bulge stars should have $v_{r,\perp} = 0$. However, there are two conflicting biases that can cause a deviation from this expected value. First, the underlying SJW sample is biased toward brighter stars and hence toward stars on the near side of the bulge. Second, the cone of observation is wider on the far side of the bulge than the near side and so contains more far-side stars. By examining the distribution of spectroscopic distances, we estimate that the median of the distribution lies $0.3 \pm 0.3$ kpc behind the peak which we identify with the galactocentric distance. The SJW sample is therefore slightly biased toward the kinematics of far-side stars. Since there are $\sim 20$ stars between the peak and the median, we estimate this bias as $\sim 20/241$ of the difference in mean proper motion of the near-side and far-side subsamples, which we evaluate as $(\Delta \mu_{\ell}, \Delta \mu_{b}) = (-0.02, 0.02) \text{mas yr}^{-1}$. Since this correction is an order of magnitude smaller than the observational errors, we ignore it and adopt $v_{r,\perp} = 0$.

We use equation (11) and apply the correction derived in equation (13) to the values of the observed (relative) proper motion given in equation (3) to obtain the absolute heliocentric proper motion

$$(\mu_{cl,\ell}, \mu_{cl,b}) = (1.4 \pm 0.2, -6.2 \pm 0.2) \text{mas yr}^{-1}. \quad (14)$$

We note that the zero-point of the frame is uncertain by $0.17 \text{mas yr}^{-1}$ in each direction due to the shot noise of the $\sim 330$ stars with scatter $\sim 3 \text{mas yr}^{-1}$ each. Assuming that the total solar motion is $v_\odot = (9, 232, 7)$ km s$^{-1}$ in the $(U, V, W)$ reference frame ($U$ being positive inwards), we evaluate equation (12), and find

$$(v_{cl,\ell}, v_{cl,b}) = (68 \pm 18, -208 \pm 23) \text{km s}^{-1}, \quad (15)$$
where we have included the distance errors, but not included the uncertainty in the overall distance scale. Finally, we evaluate the three space motion in \((U,V,W)\) reference frame,

\[
v_d = (-30 \pm 7, 68 \pm 18, -208 \pm 23) \text{ km s}^{-1}.
\]  

That NGC 6522 has a significant motion away from the Galactic plane indicates immediately that it is on a halo orbit (Cudworth & Hanson 1993), consistent with most other globular clusters which have \([\text{Fe/H}] < -1\) (Zinn 1985; Armandroff 1989). The cluster’s current distance on the Carney et al. (1995) scale \((7.1 \pm 0.3 \text{ kpc})\) is very close to the fixed Galactocentric distance of 7.8 kpc, so the cluster must be on an orbit which takes it quite near \((< 1 \text{ kpc})\) the center of the Galaxy.

We explore possible past orbits for NGC 6522 using our measurements of the cluster’s position and spatial motion. For the inner Galaxy, we assume an oblate logarithmic potential of the form

\[
\Phi(x, y, z) = \frac{1}{2} v_c^2 \ln \left[ x^2 + y^2 + (kz)^2 \right] + \text{const.},
\]

where \(v_c\) is the circular velocity in the equatorial plane (taken as 220 km s\(^{-1}\)), and \(k\) is a flattening term which we set in the range \(k = 1\) to 3. We find that about \(2 \times 10^5\) yr ago, the cluster passed the Galactic center at a distance as close as \(400 - 550\) pc, and that it generally does not achieve an apogalactic distance in excess of 1500 pc. Our calculation also shows that the time scale for significant changes to the orbital energy through dynamical friction is at least a few times \(10^{10}\) yr.

Clusters that pass within a few hundred pc of the Galactic center are likely to experience significant shocking from the time-variable gravitational potential of the bulge and inner disk (most recently Gnedin & Ostriker 1997; Murali & Weinberg 1997) and are unlikely to survive much longer than another Hubble time. NGC 6522 is also a core-collapsed cluster (e.g., Djorgovski & King 1986; Lugger et al. 1995) another sign that the cluster may have
experienced significant shocks (e.g., Gnedin & Ostriker 1997 and references therein). We therefore suggest that NGC 6522 would be a good target for detailed kinematic studies of high accuracy, to increase the number of velocity-selected members and to obtain better estimates of the mass and velocity dispersion.

Work by A.G. and P.P. were supported in part by grant AST 94-20746 from the NSF. DT thanks Ruth C. Peterson for her helpful insights.
REFERENCES


Blanco, B. M. 1984, AJ, 89, 1836


AJ, 110, 1674


Dauphole, B., Geffert, M., Colin, J., Ducourant, C., Odenkirchen, M., & Tucholke, H.-J. 

1205


---

This manuscript was prepared with the AAS B\TeX macros v4.0.
Fig. 1.— Proper motion vector point diagram for (top panel) all stars in the Baade’s Window survey (Jones et al. 1992) and (lower panel) those stars located within 2′5 of the cluster center and which have radial velocities near that of NGC 6522. The units are milliarcsecond (mas) per year. The error bars in the lower left-hand corner show the mean error of measurement in $\mu_\ell$ and $\mu_b$, plotted as though they were independent. Because the proper motions in $\ell$ and $b$ were obtained from the proper motion in right ascension and declination through a coordinate rotation, the errors in $\mu_\ell$ and $\mu_b$ are in fact correlated.

Fig. 2.— Membership probabilities in percent, as defined in the text, plotted (top) against the distance from the center of NGC 6522, and (bottom) against the $V$ magnitude. The stars we identified as cluster members have $P \geq 85\%$.

Fig. 3.— Visual extinction near NGC 6522. Shown are the values of the visual extinction $A_V$ for stars in the proper motion survey as derived from the Stanek (1996) extinction map for Baade’s Window, plotted against the difference in declination between each star and the center of NGC 6522. The extinction values have been reduced by −0.10 from the Stanek map, following the recalibration of the zero point of the extinction in Gould et al. (1998). The straight line is a least-squares fit to the data, and was used to compute reddenings within 2′ of the cluster center, an area not included in the Stanek (1996) extinction map.

Fig. 4.— Color-magnitude diagrams in Baade’s Window. The left panel shows photometry for stars within 1′5 of NGC 6522, while the right panel is for stars farther than 2′5 from the cluster center. The large filled points are for the probable cluster members in Table 1. All photometry has been corrected to $A_V = 1.42$, a value appropriate for the cluster center, as described in the text. The curved line is a quadratic fit to the cluster giant branch.

Fig. 5.— Mg$_2$ indices for SJW stars from Terndrup et al. (1995) as a function of $V − I$ color. The filled points with error bars are for the likely members of NGC 6522 in Table 1, while
the other points (×) are for the rest of the SJW sample.