

THE ABSOLUTE SPACE MOTIONS OF GALACTIC CLUSTERS: OUTER OLD OPEN CLUSTER ORIGINS

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Abstract

NASA's Space Interferometry Mission (SIM) is a satellite-based optical interferometer that will measure the positions of and distances to a strategically chosen set of stars with several scientific goals in mind, including the measurement of the mass of the Milky Way galaxy. The SIM project has chosen Galactic clusters as the best tracer of the mass distribution of the Milky Way disk. We are conducting a project to provide SIM targets, using precision radial velocities to verify cluster membership for stars in Galactic clusters. As a result of this open cluster survey, we have found that the outer most open clusters have different properties from most clusters. With further investigation, we have found that these outer, old open clusters seem to lie in an orbital plane concurrent with a newly found stellar tidal stream, and may *not* be part of Galactic disk. We present the first results of the chemo-dynamics of these, possibly accreted, clusters which will allow us to determine two things: 1) What are the properties of this new galaxy's clusters system, and 2) What are the most distant open clusters that can be used *reliably* in the study of mass distribution in the Milky Way disk.

Introduction

The NASA Space Interferometry Mission (SIM) is the first space-based mission designed to obtain high quality proper motions, velocities transverse to the line of sight, and distances to stars through stellar parallax using interferometry. This mission will produce proper motions 1000 times better than its predecessor the ESA Hipparcos mission. This project is preparatory work for a SIM key project, headed by Steven Majewski at the University of Virginia. The project aims to make use of the satellite's unprecedented positional accuracy to make several definitive measurements of fundamental structural and dynamical parameters of the Milky Way (hereafter the "Galaxy").

Because the rotation speed for stars is a function of the mass interior to the orbit, the rotation curve of a galaxy is a key method to determine its and total mass and its mass distribution. The relationship between measured rotational velocity and brightness/mass in other galaxies, known as the Tully-Fisher relation, is well determined using radio astronomy. Ironically, the measurement of

the rotation of the Galaxy is much more difficult for a variety of reasons, but primarily because our perspective from within the Galactic disk complicates matters considerably. First, we can no longer measure the net flow of all material, as in an external galaxy, but must instead find an appropriate type of object, a "tracer", thought to be most characteristic of Keplerian motion. Secondly, radii no longer trivially scale by an angular distance separation from the galactic center, but now requires us to understand the much more difficult absolute distance scale. We still do not even know the solar distance to the Galactic center to better than twenty percent. Also, the rotation speed cannot necessarily be obtained by measuring a peak Doppler velocity as a function of position, as in the Tully-Fisher measures of external galaxies. Interior to the Sun's orbit, radio astronomers can apply the "maximum velocity" tangent point method. The rotation curve is determined by measuring the peak Doppler (or radial) velocity of H I, neutral Hydrogen, in a given direction interior to the Sun's orbit as most of the rotational velocity is in the line of sight. This is done because the distance cannot be directly found for gaseous tracers, like H I.

From our viewpoint in the Galaxy, outside the solar orbit V_{rot} is almost entirely a tangential velocity (not radial) that is much harder to measure. Therefore, V_{rot} must be determined by the measurement of both radial velocities (RV) and proper motions, velocities perpendicular to the line of sight. This requires that space-based precision proper motions need to be measured. Thus, the mass of the Galaxy has been a matter of debate for over a century. Without detailed knowledge of the Galactic rotation curve, it is difficult to tie the wealth of detailed chemodynamical data we have for the Galaxy to the global dynamics established for external galaxies. This project aims to breakthrough each of these traditional problems faced in measurement of the Galactic rotation curve.

Past analyses of Galactic rotation curve studies have various tracers, including H II regions (Fich et al. 1989), Cepheid variable stars (Pont et al. 1994), and Asymptotic Giant Branch (AGB) stars and planetary nebulae (Amaral et al. 1996), but each have shortcomings. For example, gaseous tracers (planetary nebulae and H II regions) have an inherent distance scale uncertainty; AGB stars are difficult to obtain accurate photometric distances for in isolation, while pulsational variability complicates RV determination for Cepheids. Star clusters offer many ad-

Table 1: Cluster Basic Parameters

Cluster	$\alpha_{2000.0}$	$\delta_{2000.0}$	l ($^\circ$)	b ($^\circ$)
BH176	15 ^h 39 ^m 05.4 ^s	-50 [°] 03′01.7″	328.4100	+ 4.3418
Be20	05 ^h 32 ^m 37.0 ^s	+00 [°] 11′30.0″	203.4803	-17.3711
Be29	06 ^h 53 ^m 04.2 ^s	+16 [°] 55′39.0″	197.9493	+ 7.9802
Be39	07 ^h 46 ^m 51.0 ^s	-04 [°] 40′30.0″	223.5465	+10.0915
Sa1	07 ^h 20 ^m 56.0 ^s	+01 [°] 48′29.0″	214.6894	+ 7.3862

vantages over these other tracers as compared to an isolated field star at the same location in the Galaxy, because the distance, metallicity, age, and kinematics of a cluster are much easier to establish. The 3-D kinematics of individual stars or clusters requires both proper motions and RVs, but the ability to average over an ensemble of cluster members lowers the required per star precision for the same result.

This project will derive the orbits of over 100 Galactic open clusters through use of multi-fiber spectroscopy. These data are combined with the space-based Hipparcos and Tycho-2 proper motion catalogs (Dias et al. 2001, 2002a). Given the per star precisions of these catalogs, it is almost certainly the case that discrepancies compared to other work are the result of problems with identifying true cluster members, and not necessarily with the integrity of the astrometry itself. To address this problem, we have undertaken a survey to obtain precision radial velocities (RVs) to verify cluster membership for the stars used to define the cluster proper motions. The resulting very precise mean RV of each cluster, when combined with the corrected proper motions, allows us to determine the orbits of these clusters. Additionally, in the future, our radial velocities will be combined with the proper motions from SIM to yield orbits of outer Galactic clusters hundreds of times better than the current project, that will be used as dynamical probes of the Galaxy’s gravitation potential. Our survey consists of clusters selected in the range of 0.3 to 3.0 kiloparsecs (kpc) from the Sun. Half of the cluster sample was selected to cover a range of ages of 70 Megayears (Myr) to 1.2 Gigayears (Gyr). The second half of the cluster sample was selected to be at least older than 100 Myr, to ensure their dynamics have decoupled from that of their parent gas formations and are responding to the Galactic gravitational potential.

Outer Old Open Clusters and GASS

As a consequence of trying to extend this survey to cover as much of the Galactic disk as possible, we have discovered the the outer most “Galactic” open cluster may not, in fact, be part of the Milky Way disk. These distant old open clusters have been found to lie in an orbital plane concurrent with a newly discovered stellar stream believed to be tidal debris of a dwarf galaxy

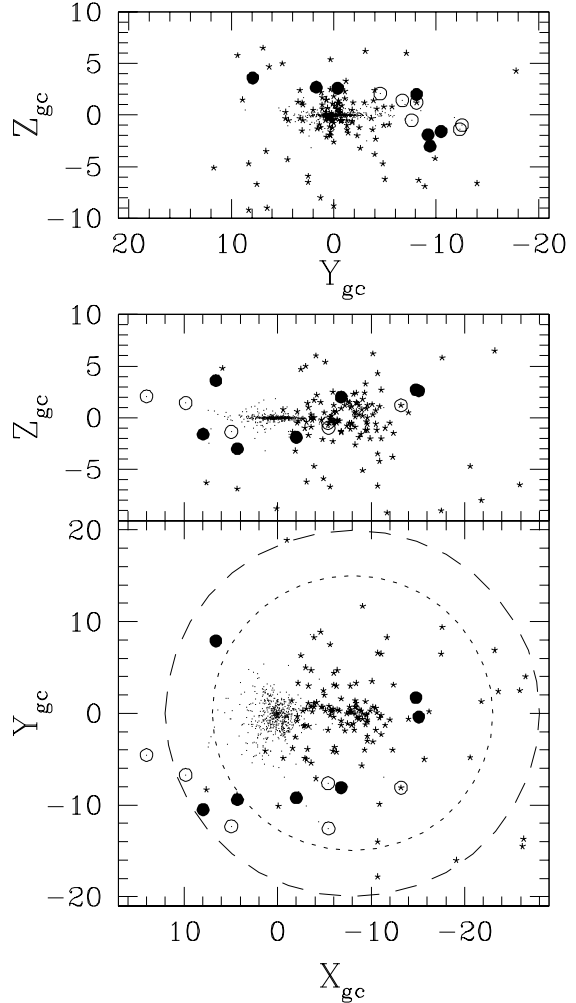


Fig. 1.— Cartesian distribution (in kpc) of clusters in the heliocentric, left-handed Galactic system (see M03). Dots show open clusters from Dias et al. (2002b), stars the globular clusters from Harris (1996). Large stars are the five GASS clusters from Crane et al. (2003). Large filled circles are the clusters with RVs consistent with GASS. Open circles show clusters spatially consistent with GASS but which do not have RVs

being eaten by the Milky Way. This structure was discovered as an excess of stars beyond the apparent limit of the Galactic disk and has been used to argue for the presence of a distinct, extended stellar structure wrapping around the disk at low latitudes and has been referred to as the Monoceros “Ring” (Newberg et al. 2002), (Yanny et al. 2003), the Canis Major galaxy (Ibata et al. 2003), and GASS (Majewski et al. 2003), (Rocha-Pinto

et al. 2003), (Crane et al. 2003). However, because of unfortunate placement behind considerable extinction, it has been difficult to get information on the system’s true shape, orientation, breadth, etc. Even the location of the structure’s center (presumably corresponding to a “nucleus”) remains uncertain (Penarrubia et al. 2004).

Previous work (Crane et al. 2003) has resulted in a number of parameters of the stream including: (1) a velocity-longitude trend indicating a slightly non-circular orbit, (2) a velocity dispersion smaller than even that of disk stars, (3) a wide metallicity spread from $[\text{Fe}/\text{H}] = -1.6 \pm 0.3$ (Yanny et al. (2003)) to at least $[\text{Fe}/\text{H}] = -0.4 \pm 0.3$. Additionally, we found in Frinchaboy et al. (2004) that five globular clusters and one open cluster, Tombaugh 2, are apparently associated with the stream based on both position and radial velocity (RV). In Frinchaboy et al. (2004), we also presented another set of clusters that were spatially consistent with GASS; however, no RVs were available for these clusters (see Figure 1). In this work, we investigate the clusters Berkeley 29 (Be29), Saurer 1 (Sa1)¹, and vdB-Hagen 176 (BH176) from Frinchaboy et al. (2004), see Table 1. These clusters did not have RVs published for the Frinchaboy et al. (2004) study, so we have obtained spectra in order to determine the cluster’s RV and whether these clusters are consistent with the observed dynamical trend of the GASS system. In addition, we obtained data for Berkeley 20 (Be20) and Berkeley 39 (Be39) for metallicity calibrations (see §4.2). These clusters will allow us to determine two things: 1) what are the properties of the GASS clusters system, and 2) what are the most distant open clusters that can be used *reliably* in the study of radial gradients in the Milky Way disk.

This study consists of three main areas, starting in §2 we analyze photometry of all of our clusters. We use our photometry to select targets for radial velocity (RV) measurements. In §3, we use these RVs to determine the clusters bulk RV that is used to confirm each clusters probability of belonging to GASS. We continue our analysis in §4 by measuring spectroscopic indices for cluster member stars with sufficient Signal to Noise (S/N). In §5 we evaluate the cluster parameters derived in §2 by incorporating membership discrimination and metallicity determination to constrain theoretical isochrones and derive improved cluster parameters. Finally in §6, we discuss the implications these clusters have for GASS as well as open cluster studies in the Galaxy.

Observations and Data Reduction

Target stars in the clusters Be20, 29, 39, Sa1, and BH176 were selected photometry presented in Frinch-

¹Originally represented as Saurer A in Frinchaboy & Phelps (2002) and Carraro & Baume (2003)

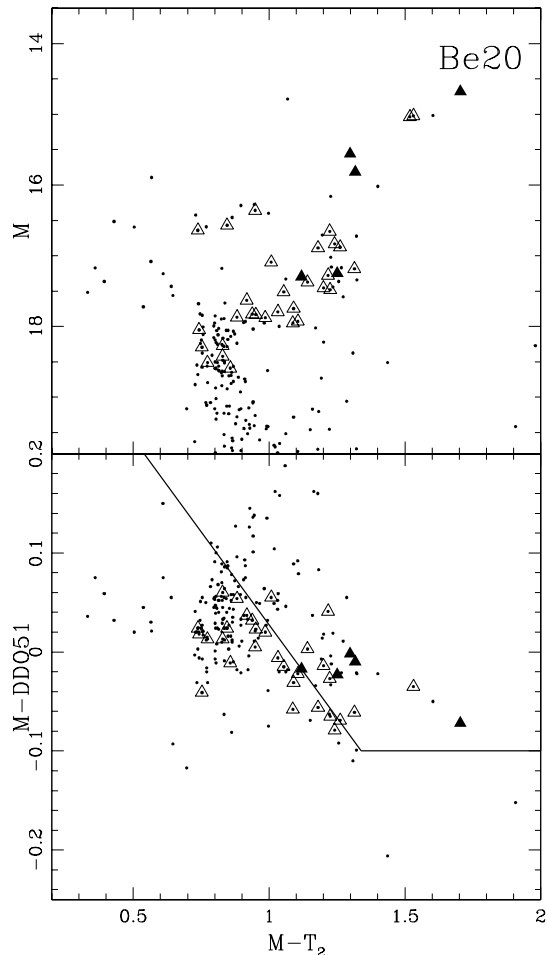


Fig. 2.— Be20 Washington+DD051 photometry color-magnitude and color-color diagrams used for spectroscopic target selection. Stars observed spectroscopically are denoted with open triangles, filled triangles denote stars selected as members.

aboy et al. (2005) and Phelps & Schick (2003). The spectra of clusters stars used for the determination of radial velocities were obtained using the multi-fiber spectrograph on the 4-m telescope at Cerro Tololo Inter-American Observatory (CTIO). The instrument uses 133 optical fibers to transfer the light from the telescope to the spectrograph. The data were taken using the Hydra multi-object spectrograph and a 2048x4096 pixel CCD (SITe400mm) on the nights of 2004 March 4–5. The spectra have a dispersion of 1.2 Å per resolution element and covered the spectral range 7700–8800 Å, with a signal-to-noise ratio (S/N) of typically 5 or better. Approximately 20–60 of the 133 available fibers were used to

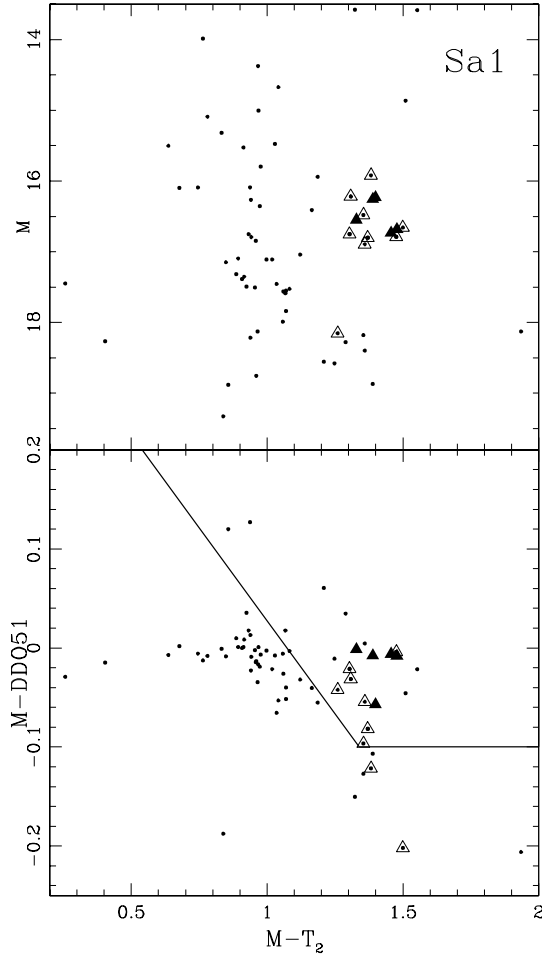


Fig. 3.— Sa1 Washington+*DD051* photometry color-magnitude and color-color diagrams used for spectroscopic target selection. Stars observed spectroscopically are denoted with open triangles, filled triangles denote stars selected a members.

observe cluster member candidates; the remaining were used for sky observations. Preliminary processing of the data was undertaken with *IRAF*² using standard techniques as described in the *IRAF* *ccdproc* documentation.

After basic processing the data were run though an *IRAF* script developed to simplify reduction to a wavelength calibrated 1-D spectrum. This script is the *dohydra* routine in *IRAF*, which prepare the spectra for

²*IRAF* is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

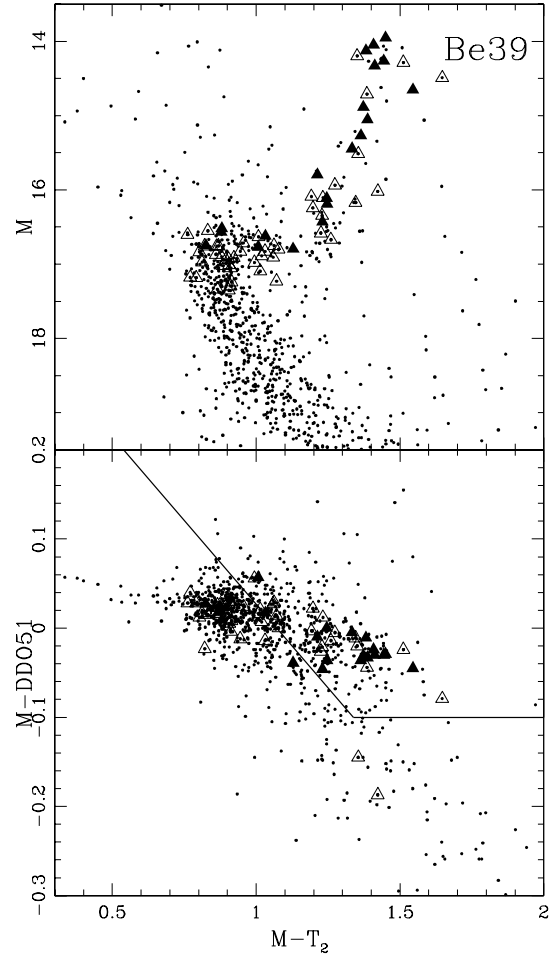


Fig. 4.— Be39 Washington+*DD051* photometry color-magnitude and color-color diagrams used for spectroscopic target selection. Stars observed spectroscopically are denoted with open triangles, filled triangles denote stars selected a members.

the *IRAF* *fxcor* cross-correlation routine described below. The script is used to perform a number of tasks. First, the spectra are transformed from a 2-D image to a 1-D spectrum by fitting a polynomial to trace of the spectrum. Next the extracted spectrum is calibrated to a comparison lamp spectrum. Exposures of a hollow cathode lamp combined with He, Ne, Ar, and Xe lamps provides a comparison spectrum yielding at least 30 comparison lines roughly evenly distributed over the wavelength range. This comparison spectrum is then used to provide a wavelength solution for the object spectrum. This solution is applied to the object spectrum. The spectrum is then dispersion corrected, which results in a resam-

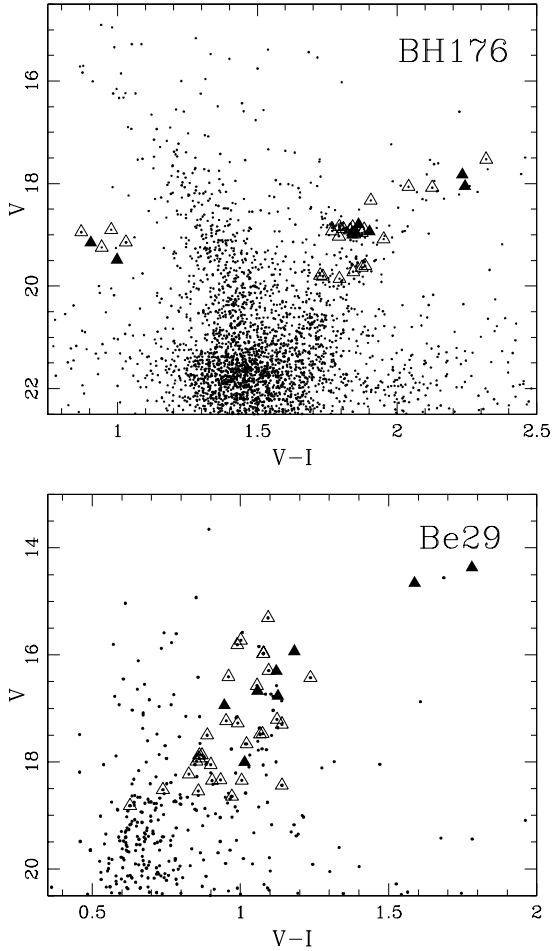


Fig. 5.— Be29 and BH176 VI photometry color-magnitude diagrams used for spectroscopic target selection. Stars observed spectroscopically are denoted with open triangles, filled triangles denote stars selected as members.

pling of the data and sky subtracts the data and standard star spectra interactively by using the *IRAF* all of the extracted spectra have the same end points and number of resulting pixels so that all of the spectra are sampled the same for input for the radial velocity determination program described below.

Radial Velocity Determination

All radial velocities were determined using *IRAF*'s *fxcor* package. *Fxcor* RVs were measured by cross-correlating the spectra against a variety of different fourier-filtered standards of late spectral type. Average velocity uncertainties for the hydra standard spectra of

$\sigma_v = 1 \text{ km s}^{-1}$ were achieved for target spectra with mean peak $S/N \geq 30$ determined from analysis of the repeated standard stars taken through multiple fibers (Table 2). The Tonry–Davis Ratio (Tonry & Davis 1979, TDR) for each spectrum were scaled to determine the radial velocity error as a function of S/N . Only stars with TDR > 5 were used for membership analysis. We found that the error could be described as in Vogt et al. (1995) using the following equation:

$$\sigma_v = \frac{\alpha^2}{(1 + TDR)} \quad (1)$$

where the constants α is calibrated from the standard stars data. Standard stars (Table 2) provided a the data set with 29 degrees of freedom; thus $\chi_{50}^2 = 28.336$ and $\alpha = 25.4$. The photometric and radial velocity results for member stars are presented in Table 3.

Membership Determination

The membership probability of star was determined by fitted a Gaussian distribution function to the data. The best fit Gaussian in radial velocity, had a full width half max (FWHM) of 3 km s⁻¹, as open clusters are known to have intrinsic velocity dispersions of less than 1 km s⁻¹ the width of the distribution was fitted to the worst cases of the measured errors in the analyzed stars. A histogram of the result heliocentric RV for these clusters are presented in Figure ?. The shaded areas denote which stars are selected as cluster members.

The stellar RVs were analyzed to determine membership. Membership determination was based on: 1) Radial Velocity, 2) Metallicity, 3) position in the CMD, 4) Position in $M - T_2$, $M - DDO51$ color-color diagram, 5) spacial position in RA and Dec, The bulk RVs were determined by measuring the mean values of the RV that are consistent with cluster membership. By averaging over an ensemble, where possible, we are able to get a more accurate measure of the clusters bulk RV.

Spectroscopic Metallicity Determinations

Index Measurements

Metallicities were determined for each star by the calibration of spectroscopic indices measuring primarily the Ca II infrared triplet, strong features centered approximately at 8498, 8542, and 8662. The indices are formed by the ratio of the average flux in a bandpass centered on the feature to that in two closely placed regions that reflect the local pseudocontinuum, expressed as a magnitude. The bandpass definitions used in this analysis are summarized in Armandroff & Zinn (1988). These features are those commonly measured in globular cluster studies and the integrated spectra of external galaxies.

Table 2: Summary of RV Standard Observations

Star	Fiber	TDR	V_r ($km\ s^{-1}$)	σ_V
HD18884	014	39.82	-26.50	1.28
	025	39.04	-26.27	1.47
	028	30.71	-27.14	1.19
	045	35.45	-26.38	1.38
	074	37.98	-26.96	1.44
	086	26.87	-26.29	1.51
	099	41.07	-26.33	1.44
	103	34.91	-26.23	1.42
	118	33.42	-26.15	1.20
	Average		-26.47	0.34
HD150798	008	46.36	-3.41	1.05
	019	47.99	-3.04	0.96
	033	35.22	-2.77	1.25
	074	40.52	-5.10	1.63
	091	40.48	-3.21	0.91
	099	42.19	-3.10	1.13
	127	34.52	-3.08	1.23
		Average		-3.39
HD157457	020	43.81	17.78	0.81
	034	34.79	17.05	0.66
	044	35.51	16.82	0.73
	045	34.56	17.50	1.37
	116	34.56	17.88	0.61
	125	30.61	18.43	1.17
	135 ^a	11.41	22.46	2.09
	Average		18.27	1.92
HD161096	030	42.29	-12.29	1.04
	038	35.49	-12.29	0.98
	039	37.83	-12.45	1.07
	040	38.85	-11.56	0.97
	048	31.59	-12.45	1.00
	057	28.02	-12.41	0.75
	077	41.44	-12.21	1.12
	098	43.22	-12.94	0.88
	104	42.25	-12.69	0.76
	110	39.67	-12.03	1.05
		Average		-12.33

^aDue to poor S/N this star was not used as a cross-correlation template

Metallicities were determined for each star in each cluster from the Ca II triplet indices with $S/N \geq 7$. All measurements were brought to the index scale established in Cole et al. (2004) by the observation of a number of stars in common from the clusters Berkeley 20 and Berkeley 39. Hydra data were resampled with a 2:1 ratio to match the Cole et al. (2004) calibration resolution (2.5 Å), yielding a resolution of 2.4 Å/resol.

Index measures were made using the code graciously made available by A. J. Cenarro³ for measuring spectral indices, especially the Ca II infrared triplet (Cenarro et al. 2001a,b). Index measurements were made, including accounting for RV errors, and applied to the Cole et

³<http://www.ucm.es/info/Astrof/ellipt/CATRIPLET.html>

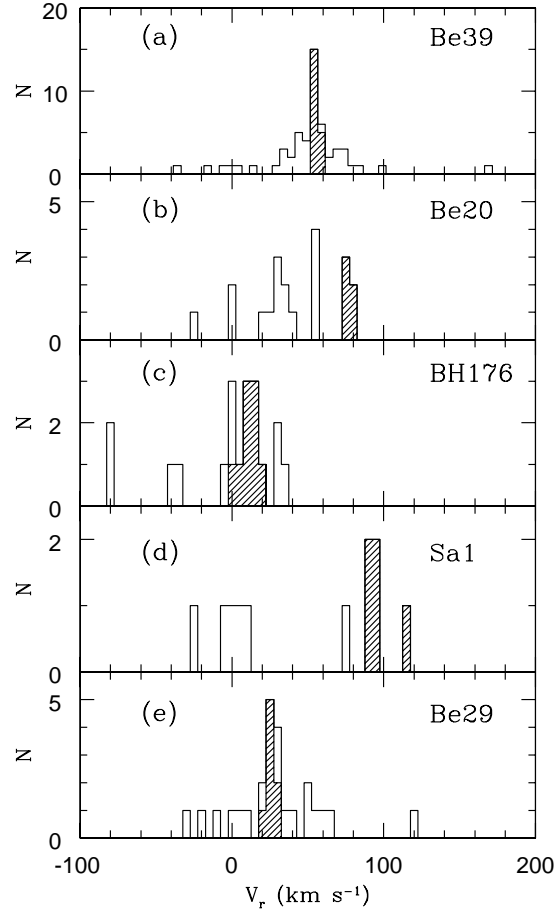


Fig. 6.— RV histograms for all clusters observed. Shaded area denote selected members.

al. (2004) system. We find a mean shift of +0.2 in W' , which in turn yields a correction of +0.1 dex in the calculated $[Fe/H]$.

Adopted Cluster Parameters

The index calibrations rest not only on the spectroscopic indices measured directly from the spectra but on the dereddened colors. For the cluster stars used to establish the calibrations, $V - I$ colors are determined from our photometry (except 47 Tuc, magnitudes from Cole et al. (2004)). As discussed below, we have used $V - I$ as a temperature indicator for the index calibration, primarily because all clusters have been observed in VI or Washington + $DDO51$ filter, which are easily transformed to the VI system Majewski et al. (2000). The stars used and the photometric values are summarized in Table 3 for the all clusters.

Sources of Error

1) The inaccuracy in the determination of the hori-

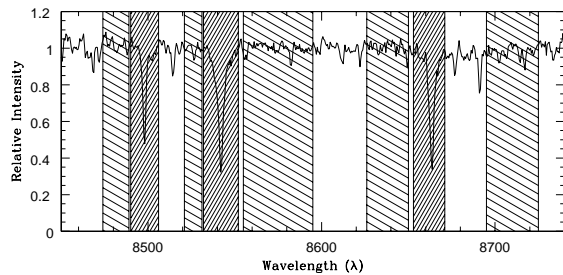


Fig. 7.— Example spectra from our survey. Indices used for metallicity measurements from Amandroff & Zinn (1988) are marked. The darker shading denotes the index bandpasses, while the lighter shading denotes the continuum bandpasses.

zontal branch for the these heavily contaminated and sparsely populated clusters. 2) Error is introduced if there is a difference in $[Ca/Fe]$ ratio (Friel 2005). As with all metallicity calibrations there remains the possibility, and often the likelihood, of zero-point errors and systematic differences as compared to other metallicity scales. Differences of 0.1 to 0.15 dex in overall $[Fe/H]$ between various studies are not uncommon, and we cannot rule out zero-point uncertainties of this magnitude here.

BH 176

We find that our RV for BH 176 is different from the single star RV presented in Frinchaboy et al. (2004). However, since we obtained good ($TD > 11$) spectra for only three stars in BH176, whose values are very discrepant, we cannot determine which of the measurements is correct. So, we refrain from any further analysis for BH176, as without spectroscopy metallicities, we cannot make any tangible improve over Phelps & Schick (2003).

Results

How the relatively high Z_{GC} -distributed, old open cluster system was formed has remained a challenging problem. Among the two most plausible models, Friel (1995) concludes that their creation during the evolution of the Galactic disk would require “fine tuning” of formation and destruction processes, whereas in an accretion model “one finds a natural mechanism for open cluster formation”, particularly for high $|Z_{GC}|$ objects. Frinchaboy et al. (2004) found that GASS clusters should be found to mimic the previously found $l - v_{GSR}$ trend (Crane et al. 2003) (Fig. 6).

While we find that the various ensemble properties of these clusters lend further circumstantial support to being part of the “tidal debris” from GASS, we agree with the

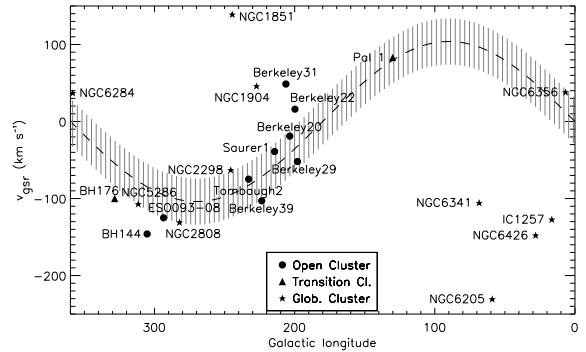


Fig. 8.— The $l - v_{GSR}$ distribution of objects lying within 2.35 kpc of the GASS cluster plane and other clusters discussed in Crane et al. (2003). Corrections to v_{gsr} assume a solar apex of $(\alpha, \delta) = (18h, 30^\circ)$ at 20.0 km s^{-1} and an LSR rotation of 220 km s^{-1} . The hash marks represent a velocity dispersion of 30 km s^{-1} about the v_{gsr} of a circularly orbiting object at $R_{GC} = 18 \text{ kpc}$ with $v_{circ} = 220 \text{ km s}^{-1}$, which approximately matches GASS M giant velocities from Crane et al. (2003).

findings of Penarrubia et al. (2004) that proper motions will be needed to discriminate which, if any, of these clusters are part coherent dynamical group. that could be consistent with the GASS/Monoceros and/or Canis Major galaxy streams.

Berkeley 29

We find that our heliocentric RV (V_r) for Be29 is in good agreement with the recent findings of Bragaglia, Held & Tosi (2005) and Carraro et al. (2004). For stars in common we find an offset of 5 km s^{-1} for Carraro et al. (2004) and $\sim 2 \text{ km s}^{-1}$ from the findings of Bragaglia, Held & Tosi (2005). The RV, when combined with the parameters in Table 5, yields a V_{gsr} of -52 km s^{-1} which places Be29 directly in the GASS l vs. V_{gsr} trend (see Figure 7), in agreement with the findings of Penarrubia et al. (2004).

Saurer 1

We find that our heliocentric RV (V_r) for Be29 is in reasonable agreement with the findings of Carraro et al. (2004). We find an offset of of the mean RV of $\sim 6 \text{ km s}^{-1}$ when compared to Carraro et al. (2004), which is based on only 2 stars. The RV, when combined with the parameters in Table 5, yields a V_{gsr} of -39 km s^{-1} which also places Sa1 directly in the GASS l vs. V_{gsr} trend (see Figure 7), in agreement with the findings of Penarrubia et al. (2004).

TABLE 3
CLUSTER MEMBER METALLICITIES

Cluster	Star	l ($^{\circ}$)	b ($^{\circ}$)	V	$(V-I)$	$V-V_{HB}$	ΣW^a (\AA)	[Fe/H] (Eq.5) ^{a,b}	[Fe/H] (Eq.6) ^{a,b}
Be20	10770	05:32:37.93	00:11:09.8	14.73	1.521	-1.4	6.7	-0.4	-0.5
	10810	05:32:39.20	00:10:31.3	15.69	1.196	-0.4	5.8	-0.7	-0.9
	10851	05:32:41.53	00:10:02.9	15.94	1.212	-0.2	5.9	-0.7	-0.9
Be29	822	06:53:01.47	16:55:01.9	16.30	1.121	-0.4	6.7	-0.4	-0.5
	868	06:53:03.87	16:55:15.9	14.66	1.588	-2.0	6.5	-0.5	-0.6
	1000	06:53:04.37	16:55:54.3	14.37	1.781	-2.3	7.3	-0.2	-0.1
	1426	06:52:49.66	16:58:57.0	15.93	1.182	-0.8	6.3	-0.6	-0.7
	1437	06:53:12.25	16:59:01.3	16.77	1.126	+0.1	5.1	-1.0	-1.3
Be39	20289	07:46:12.10	-4:39:05.3	14.95	1.233	+0.5	6.9	-0.4	-0.3
	20685	07:46:25.30	-4:40:33.9	16.91	1.038	+2.5	7.8	-0.0	+0.2
	21054	07:46:34.82	-4:41:14.3	16.52	1.120	+2.1	6.6	-0.5	-0.5
	21091	07:46:35.88	-4:40:38.9	16.68	0.840	+2.3	7.3	-0.2	-0.1
	21152	07:46:37.18	-4:40:11.4	14.00	1.295	-0.4	7.0	-0.3	-0.3
	21206	07:46:38.58	-4:39:21.6	16.20	1.131	+1.8	7.4	-0.2	-0.1
	21365	07:46:41.27	-4:40:56.9	14.31	1.290	-0.1	7.1	-0.3	-0.3
	21606	07:46:46.04	-4:38:58.4	16.28	1.132	+1.9	7.6	-0.1	+0.1
	21815	07:46:49.13	-4:41:55.5	15.34	1.226	+0.9	7.3	-0.2	-0.1
	21912	07:46:50.77	-4:41:28.7	14.11	1.261	-0.3	6.7	-0.4	-0.5
	21925	07:46:51.15	-4:40:29.1	14.68	1.371	+0.3	6.7	-0.5	-0.5
	22013	07:46:52.51	-4:41:14.5	14.39	1.264	-0.0	7.4	-0.2	-0.1
	22144	07:46:55.21	-4:36:51.1	15.89	1.105	+1.5	7.8	-0.0	+0.2
	22154	07:46:55.11	-4:39:27.2	15.12	1.244	+0.7	6.9	-0.4	-0.3
	22584	07:47:04.94	-4:35:42.3	15.52	1.201	+1.1	7.4	-0.2	-0.1
	22989	07:47:16.75	-4:39:15.0	14.19	1.240	-0.2	7.2	-0.3	-0.2
	BH176	4190	15:39:00.03	-50:04:16.3	17.83	2.234	-1.0	7.7	-0.1
4245		15:39:00.24	-50:01:33.1	19.16	0.904	+0.3	9.5	+0.6	+1.3
9312		15:39:12.70	-50:01:59.9	18.05	2.243	-0.8	6.3	-0.6	-0.7
Sa1	311	07:21:00.52	01:45:07.0	16.87	1.231	-0.1	6.0	-0.7	-0.9
	521	07:20:52.79	01:47:19.4	16.76	1.151	-0.2	6.4	-0.5	-0.6

^a0.2 added to W^* due to systematic offset with Cole et al. (2004), applied before calculation of [Fe/H]

^bEquations for calculating [Fe/H] are from Cole et al. (2004)

TABLE 4
BULK CLUSTER RADIAL VELOCITIES AND METALLICITIES

Cluster	W^* (\AA)	[Fe/H] (Eq.5) ^a	[Fe/H] (Eq.6) ^a	[Fe/H] (Pub.)	V_r (km s^{-1})	σ_V (km s^{-1})	$V_{r,pub}$ (km s^{-1})	$\sigma_{V_r,pub}$ (km s^{-1})	Reference. ([Fe/H],RV)
Berkeley 20	6.73 ± 0.10	-0.6 ± 0.30	-0.7 ± 0.30	1.99	75.7	0.5	78.0	3.0	1,1
Berkeley 29	6.61 ± 0.10	-0.5 ± 0.30	-0.6 ± 0.30	1.99	26.6	0.4	24.6	0.1	2,2
Berkeley 39	7.41 ± 0.10	-0.3 ± 0.10	-0.2 ± 0.10	1.99	55.7	0.2	58.0	3.0	1,1
Saurer 1	6.38 ± 0.10	-0.5 ± 0.30	-0.6 ± 0.30	1.99	98.0	1.0	104.0	0.1	2,2
BH 176	11.2	0.5

References. —1. Carraro et al. (2004), 2. Friel et al. (2002)

^aEquations for calculating [Fe/H] are from Cole et al. (2004)

TABLE 5
BULK CLUSTER PARAMETERS

Cluster	Log(Age)	d_{\odot} (kpc)	R_{gc} (kpc)	$E(V-I)$	[Fe/H] _{spec}	V_r (km s^{-1})	V_{gsr} (km s^{-1})	GASS?
Berkeley 29	9.54	13.5	22.6	0.1	-0.6	+26.6	-52.0	Yes
Saurer 1	9.70	13.0	19.1	0.2	-0.6	+98.6	-39.0	Yes
BH 176 ^a	9.85	14.8	9.7	0.7	...	+11.2	-100.0	??

^aAll parameters except V_r and V_{gsr} are from Phelps & Schick (2003)

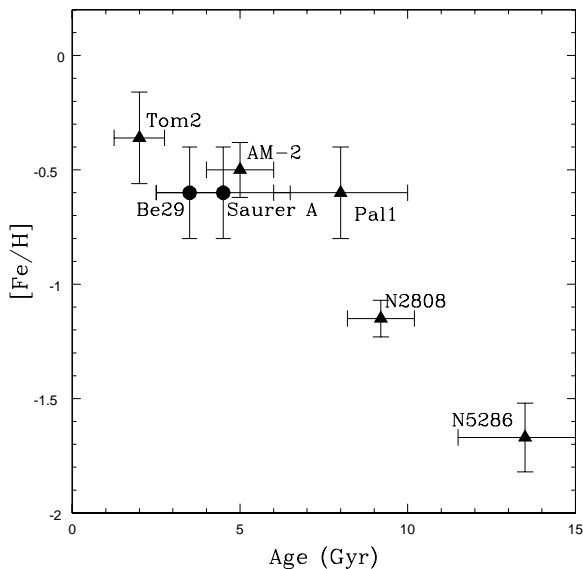


Fig. 9.— Age-metallicity relation (AMR) for confirmed GASS clusters

BH176

We find a new RV for BH 176, which is marginally consistent with membership in GASS. We agree with the findings of Forbes, Strader & Brodie (2004) that based on current *photometrically* determined $[Fe/H]$ the BH176 should not belong to GASS; however, we note that until spectroscopic measurements are done it cannot be definitively ruled out either. If BH176 is found to have $[Fe/H] \sim 0.0$, and is actually a globular cluster as it has been cataloged (Harris 1996), further investigation is needed as BH176 could provide important constraints on Galactic halo formation scenarios.

Connections to GASS/Monoceros stream and Revised Age-Metallicity Relation

The arcing spatial sequence and planar alignment is tantalizingly suggestive of an origin relating to the interaction of a satellite galaxy with the Milky Way — either through the stripping of star clusters from a tidally disrupting dwarf galaxy, or through the *formation* of clusters as gas from the dwarf collides with molecular clouds of the Galactic disk.

To compare with other dwarf galaxies that have clusters, we re-derive an age-metallicity relation (Frinchaboy et al. 2004) for those clusters that are consistent with GASS, in spatial V_{gsr} parameter space, *and* for which *spectroscopic* metallicities have been derived. We compare this relation to that of the old open cluster system of the Milky Way, as well as, to dwarf galaxy with clusters in the local group. Be29, Sa1, Tombaugh 2, Arp-Madore 2, Palomar 1, NGC2808 and NGC 5286 are the

remaining clusters with RVs from the lists in Crane et al. (2003) and Frinchaboy et al. (2004) currently found to be consistent with GASS. We find that the AMR for these clusters is similar to that of the Fornax (For) and Sgr satellite galaxies. These galaxies have clusters with sizes and luminosities (e.g., Mackay & Gilmore 2003) that span those of the typical old open cluster (Friel 1995) and young globular clusters. Fig. 7 shows an AMR of the GASS cluster system, which is typical of that expected for an independently evolving, “closed-box” system with protracted star formation. Layden & Sarajedini (2000) Fig. 18 shows the AMR of stars and clusters in the Sagittarius dSph system, which also mimics that of a “closed-box” system. As noted in Frinchaboy et al. (2004), these clusters are outliers of the old Galactic open clusters AMR shown in Fig. 8 of Friel (1995).

We find that Be29 and Sa1 are members of the GASS cluster system, based on their kinematics and chemistry, in confirmation with the findings of Carraro et al. (2004)⁴ and Penarrubia et al. (2004)

Future Work

Future work on this project is to extend the analysis to the complete cluster sample. More than 100 clusters have been observed. These clusters will be used to not only measure their orbits, but, once the ensemble is complete, to test the Galactic model used in the orbit integration and thereby the mass and mass distribution of the Galactic disk and the GASS.

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⁴We find Sa1 to be a member due to its V_{gsr} ; Carraro et al. (2004) did not correct this RV to V_{gsr} before incorrectly excluding it from the GASS member clusters

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