

## STAR CLUSTERS IN THE GALACTIC ANTICENTER STELLAR STRUCTURE AND THE ORIGIN OF OUTER OLD OPEN CLUSTERS

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Received 2003 October 12; accepted 2004 January 5; published 2004 January 30

### ABSTRACT

The Galactic anticenter stellar structure (GASS) has been identified with excess surface densities of field stars in several large-area sky surveys and with an unusual, stringlike grouping of five globular clusters. At least two of these are diffuse, young “transitional” clusters between open and globular types. Here we call attention to the fact that four *younger* open or transitional clusters extend the previously identified, stringlike cluster grouping, with at least one having a radial velocity consistent with the previously found GASS velocity-longitude trend. All nine clusters lie close to a plane tipped  $17^\circ$  to the Galactic plane. This planar orientation is used to forage for additional potential cluster members in the inner Galaxy, and a number are found along the same plane and stringlike sequence, *including almost all 15 known outer, old open clusters*. Tidal accretion of a dwarf satellite galaxy on a low-inclination orbit—perhaps the GASS system—appears to be a plausible explanation for the origin of the outer, old open and transitional clusters of the Milky Way. We use these clusters to explore the age-metallicity relation of the putative accreted GASS progenitor. Finally, we provide the first radial velocity of a star in the cluster BH 176 and discuss its implications.

*Subject headings:* galaxies: interactions — Galaxy: disk — Galaxy: structure — globular clusters: general — open clusters and associations: general

### 1. INTRODUCTION

Excesses of stars beyond the apparent limit of the Galactic disk have been used to argue for the presence of a distinct, extended stellar structure wrapping around the disk at low latitudes (Newberg et al. 2002; Ibata et al. 2003, hereafter I03; Majewski et al. 2003; Yanny et al. 2003, hereafter Y03; Rocha-Pinto et al. 2003, hereafter R03). Collectively, these surveys suggest that the structure spans  $|b| < 30^\circ$  and at least  $122^\circ < l < 225^\circ$  at a mean  $R_{GC} \sim 16$  kpc (I03; R03) and radial thickness  $\lesssim 4$  kpc (Y03; I03). 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; thus we refer to the entire system here as the Galactic anticenter stellar structure (GASS).

The origin of the GASS—originally described as a “ring” around the Galaxy (I03; Y03)—is also not definitively established, with a number of potential scenarios outlined, e.g., by I03: a tidally disrupted satellite galaxy, an outer spiral arm, or (their preference) a resonance induced by an asymmetric Galactic component. From among possibilities involving accretion, Helmi et al. (2003) explore the extremes of dynamically young and old tidal debris, and Crane et al. (2003, hereafter C03) argue, as did Y03 earlier, that the most straightforward interpretation is that the GASS is a disrupted satellite galaxy, resembling in many ways the Sagittarius (Sgr) dwarf galaxy (e.g., Majewski et al. 2003) system. As evidence, C03 point to (1) a velocity-longitude trend indicating a slightly noncircular orbit, (2) a velocity dispersion smaller than even that of

thin-disk stars, (3) a wide metallicity spread from  $[Fe/H] = -1.6 \pm 0.3$  dex (Y03) to at least  $-0.4 \pm 0.3$  dex, and (4) at least four star clusters apparently associated with the stream based on position *and* radial velocity (RV). These clusters (Pal 1, NGC 2808, NGC 5286, and NGC 2298), plus a fifth having no RV measurement (BH 176), lie in an unusual, arclike configuration not seen elsewhere among low-latitude outer globular clusters (GCs), but one resembling configurations expected for tidal debris systems (e.g., Bellazzini, Ferraro, & Ibata 2003).

Several unusual GCs are identified by C03 as potential GASS members. Pal 1 is both very small ( $M_V = -2.5$ ) and relatively metal-rich ( $[Fe/H] = -0.6$ ) for an  $R_{GC} > 8$  kpc GC. Rosenberg et al. (1998) derive a Pal 1 age of  $8 \pm 2$  Gyr and suggest it is either the youngest GC or one of the oldest open clusters (OCs) in the Galaxy. Phelps & Schick (2003) find BH 176 to be young ( $7.0 \pm 1.5$  Gyr) and metal-rich ( $-0.20 \leq [Fe/H] \leq +0.20$ ) and suggest it is “transitional” between a young, metal-rich GC and a massive, metal-rich old OC.

Prompted by this hint that the GASS may contain younger, more metal-rich star clusters, and by our new distance for OC Saurer A (Sau A; Frinchaboy & Phelps 2002) placing it near the R03 and C03 tracings of the GASS, we search here for other *open clusters* coincident with the GASS and find an interesting potential connection with the Milky Way (MW) old OC system.

### 2. RADIAL VELOCITY OF A BH 176 GIANT CANDIDATE

Because BH 176 has no measured RV to check against the apparent  $l-v_{GSR}$  trend of the GASS, observations of candidate BH 176 giant stars were obtained with the Ritchey-Chrétien spectrograph and 600 line  $\text{mm}^{-1}$  grating (4.3 Å per resolution element) on the Cerro-Tololo Inter-American Observatory 1.5 m telescope on UT 2003 August 2. Three obvious stars along the BH 176 red giant sequence, redder than the typical field stars and at the cluster center, were selected from the Ortolani, Bica, & Barbay (1995) database. However, only the spectrum of the star at  $(\alpha, \delta) = (15^{\text{h}}39^{\text{m}}07^{\text{s}}.8, -50^\circ03'11'')$  (J2000.0) proved

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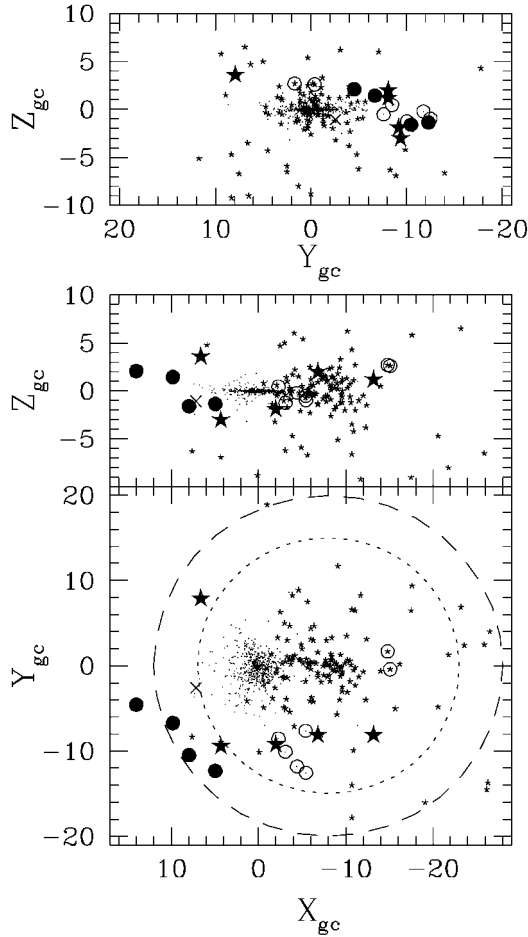


FIG. 1.—Cartesian distribution (in kiloparsecs) of clusters in the heliocentric, left-handed Galactic system (see Majewski et al. 2003). *Dots*: Open clusters from Dias et al. (2002). *Stars*: GCs from Harris (1996). *Large stars*: Five GASS clusters from C03. *Large filled circles*: Four new GASS cluster candidates discussed in § 3. *Open circles*: Seven GASS clusters selected by plane-fitting (§ 4). *Cross*: Berkeley 22 (see § 5).

of sufficient quality for a reliable RV. The spectrum from 4400 to 5240 Å was cross-correlated against spectra of stars Gl 803 (spectral type M0) and Gl 643 (M3.5), using both IRAF’s FXCOR task and our own software (C03). Weak MgH + Mg *b* absorption in the spectrum of the target star strongly suggests that it is a giant (of spectral type M2–M3). An average  $v_{\text{hel}} = 85 \text{ km s}^{-1}$  is obtained, where a  $30 \text{ km s}^{-1}$  error is estimated from the spread of results using different RV standards and software. While not highly precise, and of only one giant star in the cluster field, the  $v_{\text{GSR}} = -27 \pm 30$  for this star tantalizingly suggests (if it is a BH 176 member) that BH 176 follows the  $l$ - $v_{\text{GSR}}$  trend of the GASS (C03; see Fig. 2 below). Therefore, we include BH 176 among more likely GASS clusters.

### 3. DISTANT OPEN CLUSTERS CORRELATED WITH GASS

Figure 1 shows the distribution of OCs (using the on-line database by Dias et al. 2002, updated as in Table 1) and GCs (from the latest on-line compilation by Harris 1996). The five GASS cluster candidates from C03 are marked by large star symbols.<sup>4</sup> The four OCs with  $R_{\text{GC}} > 15 \text{ kpc}$  (AM 2, Tombaugh 2, Berkeley 29, and Sau A) are *also* exceptional for lying in a stringlike configuration (Fig. 1, *large circles*). The unusual  $R_{\text{GC}}$  values of the first three have long been recognized (e.g., Adler & Janes 1982; Kaluzny 1994; Ortolani et al. 1995), but the extreme  $R_{\text{GC}}$  of Sau A has only recently been noted (Frinchaboy & Phelps 2002). Considering spatial biases in the known OC sample (due, e.g., to extinction), four clusters in one part of the sky might not be considered too unusual. However, these four extreme OCs also lie along the GASS M giants (see Fig. 4 of R03 and Fig. 1 of C03) and extend the spatial trend of the GASS GCs from C03. Moreover, Tombaugh 2’s measured RV,  $v_{\text{GSR}} = -74.8 \text{ km s}^{-1}$ , places it squarely on the  $l$ - $v_{\text{GSR}}$  trend observed for GASS stars and clusters (Fig. 2). In addition, Sau A (Frinchaboy & Phelps 2002; Carraro & Baume 2003) and AM 2 (Lee 1997; Ortolani et al. 1995) have ages and metallicities (Table 1) similar to those of Pal 1. AM 2, like BH 176 and Pal 1, has been discussed as a possible “transitional

<sup>4</sup> The GCs NGC 1851 and NGC 1904 lie along the same  $X_{\text{GC}}$ - $Y_{\text{GC}}$  cluster trend and are coincident with the R03 tracing of GASS, but C03 show them to have RVs and/or  $Z_{\text{GC}}$  values discordant with those of the GASS M giants and five other GCs.

TABLE 1  
CLUSTER DATA

Cluster	Type	$l$ (deg)	$b$ (deg)	$R_{\text{GC}}$	$d_{\odot}$	$X_{\text{GC}}$	$Y_{\text{GC}}$	$Z_{\text{GC}}$	Age	[Fe/H]	$v_{\text{GSR}}$	$M_V$	DP	Notes
Pal 1	TC	130.07	19.03	17.00	10.90	6.60	7.90	3.60	8.00	-0.60	-107.0	-2.47	-1.06	1
NGC 2298	GC	245.63	-16.01	15.70	10.70	4.30	-9.40	-3.00	12.59	-1.85	-62.8	-6.30	-2.35	2
NGC 2808	GC	282.19	-11.25	11.10	9.60	-2.00	-9.20	-1.90	9.12	-1.15	-130.8	-9.39	-1.72	2
NGC 5286	GC	311.61	10.57	8.40	11.00	-7.20	-8.10	2.00	...	-1.67	-107.0	-8.61	-1.06	
BH 176	TC	328.41	4.34	9.70	15.60	-13.20	-8.10	1.20	7.00	0.00	-27.0	-4.35	1.12	3
Arp-Madore 2	TC	248.12	-5.87	17.91	13.34	4.94	-12.31	-1.36	5.00	-0.50	...	...	0.11	4
Berkeley 29	OC	197.98	8.02	22.56	14.87	14.00	-4.54	2.07	1.06	-0.18	...	-4.64	1.60	5
Saurer A	OC	214.31	6.83	19.08	11.97	9.81	-6.70	1.42	7.20	-0.50	...	...	1.38	6
Tombaugh 2	OC	232.83	-6.88	19.15	13.26	7.95	-10.49	-1.58	2.00	-0.36	-74.0	...	-0.47	
ESO 092-18	OC	287.12	-6.65	11.26	10.60	-3.11	-10.06	-1.22	1.05	...	...	...	-0.88	
ESO 093-08	TC	293.50	-4.04	12.82	13.70	-5.46	-12.53	-0.96	4.47	-0.40	...	...	0.02	3
Saurer C	OC	285.09	2.99	10.25	8.83	-2.30	-8.51	0.46	2.82	...	...	...	0.31	
Shorlin 1	OC	290.56	-0.92	12.32	12.60	-4.43	-11.79	-0.20	...	...	...	...	0.53	
BH 144	OC	305.34	-3.15	8.06	9.35	-5.46	-7.61	-0.51	0.67	...	...	...	-1.06	
NGC 6284	GC	358.35	9.94	7.60	15.30	-15.10	-0.40	2.60	...	-1.32	37.2	-7.97	-0.78	
NGC 6356	GC	6.72	10.22	7.60	15.20	-14.80	1.70	2.70	...	-0.50	38.1	-8.52	-1.29	

NOTES.—All distances (including “DP,” the distance from the plane defined in § 3) are in kiloparsecs, ages are in gigayears, and  $v_{\text{GSR}}$  is in kilometers per second. All values are from Harris 1996 or Dias et al. 2002 except as noted: (1) age from Rosenberg et al. 1998; (2) age from Salaris & Weiss 2002; (3)  $d_{\odot}$ , age, [Fe/H] from Phelps & Schick 2003; (4) age, [Fe/H] from Lee 1997; (5)  $M_V$  from Lata et al. 2002; (6) [Fe/H] from Carraro & Baume 2003.

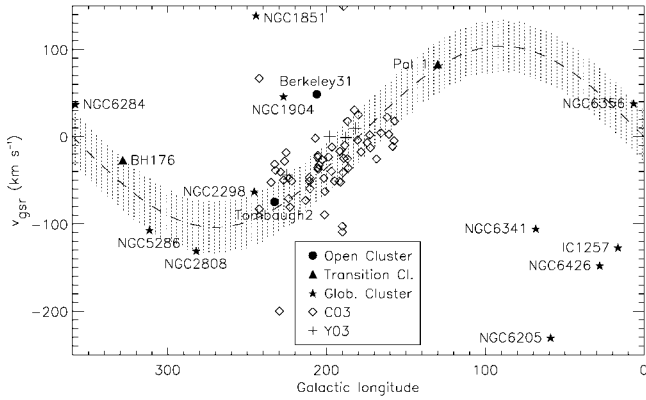


FIG. 2.—The  $l$ - $v_{\text{GSR}}$  distribution of objects lying within 2.35 kpc of the GASS cluster plane and other clusters discussed in C03. Corrections to  $v_{\text{GSR}}$  assume a solar apex of  $(\alpha, \delta) = (18^{\text{h}}, 30^{\circ})$  at  $20.0 \text{ km s}^{-1}$  and an LSR rotation of  $220 \text{ km s}^{-1}$ . The hatch marks represent a velocity dispersion of  $30 \text{ km s}^{-1}$  about the  $v_{\text{GSR}}$  of a circularly orbiting object at  $r_{\text{GC}} = 18 \text{ kpc}$  with  $v_{\text{circ}} = 220 \text{ km s}^{-1}$ , which approximately matches GASS M giant velocities.

cluster” (TC) by Ortolani et al. (1995). These similarities strongly suggest these four “open” clusters may also be associated with the GASS.

These nine “primary” GASS candidate clusters—although spread over dozens of kiloparsecs, three Galactic quadrants, and  $-3.0 \text{ kpc} < Z_{\text{GC}} < +3.6 \text{ kpc}$  (Table 1 gives adopted coordinates)—also lie close to a single, inclined plane: a least-squares fit finds all nine within 2.35 kpc of  $0.057X_{\text{GC}} - 0.297Y_{\text{GC}} + 0.953Z_{\text{GC}} = 2.521$ , with an rms of only 1.39 kpc. Because these nine clusters were first identified on the basis of their  $X_{\text{GC}}$ - $Y_{\text{GC}}$  configuration (although, admittedly, clusters with extreme  $Z_{\text{GC}}$  were ruled out by C03), and further winnowing of the sample relied only on available RVs (C03), there should be no reason to expect these clusters to lie as close to one plane as they do; yet this rms is smaller than that for association with the *Galactic* plane (GP): 2.15 kpc. Cohesion to this plane [with pole  $(l, b) = (79^{\circ}2, -72^{\circ}7)$ ] is further support for dynamical association of these clusters.

#### 4. FORAGING FOR OTHER POTENTIAL MEMBERS

The alignment of the nine primary GASS clusters can be extrapolated to search for additional associated clusters in the more crowded inner Galactic regions. This exercise, while intended simply to identify other interesting possible members for future study, does turn up an interesting coincidence (§ 5). For now we exclude consideration of (1) the many clusters with  $d_{\odot} < 7 \text{ kpc}$ , many of which, by chance, fall near the GASS cluster plane because its line of nodes with the GP lies nearby, and (2) the populous “disk” GC system with  $R_{\text{GC}} < 7 \text{ kpc}$ . Adopting this conservative “volume of avoidance” is consistent with (1) an expectation that, if tidal debris, the GASS must arc to the other side of the Galactic center and (2) a presumption, based on the  $X_{\text{GC}}$ - $Y_{\text{GC}}$  distribution of the GASS clusters and M giants, along with the C03 velocities, that the GASS orbit is only slightly elliptical with perigalacticon  $\geq 7 \text{ kpc}$ . A search through the cluster catalogs for other objects within 2.35 kpc of the best-fit plane (2.35 kpc is the largest deviation of the nine plane-defining clusters) yields six more OCs and six more GCs.

The total sample of 21 clusters have an rms of only 1.03 kpc about the § 3 plane and represent an overdensity of clusters along any plane. Statistical tests of the parent sample and scrambled

versions thereof find randomly placed planes to typically have only 8.2 clusters within 2.35 kpc. The cluster catalogs were scrambled to preserve the combined density law and discovery function (and tested with the volume of avoidance above): GCs were randomly rotated about the  $Z$ -axis through the Galactic center, preserving  $R_{\text{GC}}$  and  $Z_{\text{GC}}$ , while OCs were randomly rotated about the  $Z_{\text{GC}}$ -axis, preserving  $Z_{\text{GC}}$  and  $d_{\odot}$ . The tests show that the probability of finding 20 or more clusters in a Poisson distribution with a mean of only 8.2 is 0.04%. However, these statistics also suggest that  $8 \pm \sqrt{8}$  chance “interlopers” lie among the 21 clusters. Seven of the new clusters have RVs useful to prune (as in C03) to the most interesting candidates based on correlation with the previously found  $l$ - $v_{\text{GSR}}$  trend (Fig. 2). Thus, we “demote” as less likely to be associated the GCs NGC 6205, NGC 6341, NGC 6426, and IC 1257 and the OC Berkeley 31, but find the GCs NGC 6284 and NGC 6356 to nicely fall along the Figure 2 trend. The latter two GCs, together with the five new clusters without RVs plus nine primary GASS clusters (i.e., all clusters in Table 1), collectively define an asymmetric distribution in space. For example, 14 of the 16 clusters have  $Y_{\text{GC}} < 0$  and almost all define an arcing sequence in various Figure 1 projections, strengthening the impression of an inclined, tidal tail-like trail in three-dimensional space (Fig. 1). The seven new candidate clusters are actually *even more* tightly confined to the nominal plane (rms = 0.81 kpc, and with all clusters within 1.3 kpc) than are the nine clusters that defined it (rms = 1.39 kpc)! The net rms about the § 3 plane for all Table 1 clusters is 1.15 kpc.

Despite some affinity of the outer clusters for the GP, only 16 from the parent population have  $Z_{\text{GC}} < 2.35 \text{ kpc}$ , and these with a larger rms( $Z_{\text{GC}}$ ) = 1.31 kpc. Thirteen of these 16 “GP clusters” overlap with the sample of 21 above. The probability of finding more than 21 clusters in a plane from a parent population whose average is 16 is 13.2%. While it might still be argued that the § 3 plane merely reflects a concentration of clusters in the GP, given the *stronger* cluster alignment along the § 3 plane, it seems a fair (and as we show below, *interesting*) exercise to at least consider the converse supposition.

#### 5. DISCUSSION

How the relatively high  $Z_{\text{GC}}$ -distributed, old OC system was formed has remained a challenging problem. Among the two most plausible models, Friel (1995) concludes that old OC creation during evolution of the MW disk requires “fine tuning” of formation and destruction processes, whereas in accretion “one finds a natural mechanism for open cluster formation,” particularly the high- $|Z_{\text{GC}}|$  OCs. In this context we find several interesting coincidences regarding the 15 known OC/TC objects with  $d_{\odot} > 7 \text{ kpc}$  and  $R_{\text{GC}} > 7 \text{ kpc}$ : (1) Remarkably, 13 of these 15 clusters are confined to the third and fourth Galactic quadrants, something that would occur by chance only 4.3% of the time. Such a lopsided distribution is easily accommodated by an accretion origin but not by a disk formation model. (2) Eleven of these 15 clusters are among the GASS candidate clusters in Table 1, while one more, Berkeley 22, lies right in the M giant GASS tracing by R03 and would have been included in our sample had we used a planar distance limit only 20 pc larger. Although clearly old (0.7–7 Gyr) for OCs, the Table 1 TC/OC objects are generally poorly studied and have unknown RVs; their proposed association with one another and with the GASS field star overdensities must therefore be considered tentative. Nevertheless, their arcing spatial sequence and planar alignment (§ 4) are tantalizingly suggestive of an

origin relating to the interaction of a satellite galaxy with the MW.

An alternative view might hold that the arcing spatial sequence of star clusters and the correlated overdensities of field stars defining the GASS merely represent an outer MW spiral arm. However, if a spiral arm, it is strangely inclined by  $17^\circ$  to the GP. In addition, spiral arms characteristically have *young* star clusters, yet no Table 1 cluster is younger than 0.67 Gyr. There is also no GASS correlation with the Galactic warp (C03).

On the other hand, star clusters in the Fornax (For) and Sgr satellite galaxies have sizes and luminosities (e.g., Mackay & Gilmore 2003) that span those of the typical old OC (Friel 1995) and Table 1 objects; that For and Sgr clusters are called “globular” seems mainly to reflect a difference in age, but *young* clusters of similar  $M_V$  are prevalent (Hunter et al. 2003) in the Magellanic Clouds (MCs). Under the premise that the Table 1 objects represent the cluster system of a dwarf galaxy, one can use them to explore the age-metallicity relation (AMR) of that putative system. Figure 3 shows an AMR typical of that expected for an independently evolving, “closed box” system with protracted star formation (compare Fig. 3 to the similar AMR of Sgr field stars and clusters in Fig. 18 of Layden & Sarajedini 2000). Apart from BH 176, the Figure 3, outer TC/OC clusters show a relatively tight AMR (even including Be 22), especially compared to that for *all* old MW OCs (e.g., Fig. 8 of Friel 1995) and to the LMC cluster AMR (e.g., Fig. 2a of Bica, Dottori, & Pastoriza 1986). A large metallicity spread among these clusters mimics the spread among noncluster GASS stars discussed by C03. Together, the various ensemble properties of the GASS clusters lend further circumstantial support to the “tidal debris” explanation for the GASS. However, while having an AMR similar overall to that of Sgr, the GASS appears to have star clusters much younger than in the MW-accreting cluster system of Sgr, for which the youngest and most metal-rich known cluster is Terzan 7 (age =  $8.3 \pm 1.8$  Gyr,  $[\text{Fe}/\text{H}] = -0.82 \pm 0.15$ ; Layden & Sarajedini 2000). Clearly such differences in the selective production and/or destruction of clusters within MW satellites is not a problem since differences in the distribution of

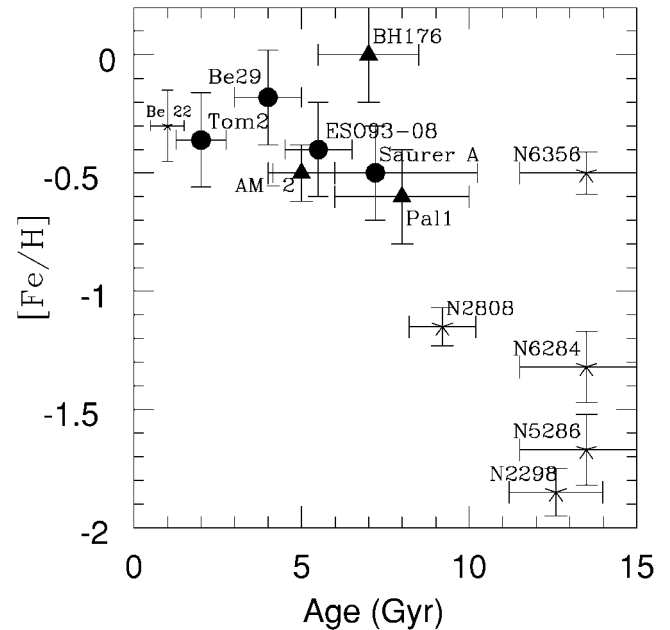


FIG. 3.—AMR of Table 1 clusters plus Be 22 (see § 5). Symbols are the same as in Fig. 2.

cluster ages are already observed between the systems in For, Sgr, and the MCs, all galaxies with continuing star formation up to the near present. But the lower inclination and apparently smaller orbit of the GASS compared to these other MW satellites suggests consideration of an additional mechanism for the constant production of new star clusters through the continuous interaction of a “GASSeous” dwarf galaxy with the gaseous disk of the MW.

We acknowledge funding by NSF grant AST 03-07851, NASA/JPL contract 1228235, the David and Lucile Packard Foundation, and the Celerity Foundation.

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