DIAMETERS OF OPEN STAR CLUSTERS

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ABSTRACT

The present paper presents a tabulation of data on all 600 Galactic open clusters for which it is currently possible to calculate linear diameters. As expected, the youngest "clusters," with ages <15 Myr, contain a significant ($\geq$20%) admixture of associations. Among intermediate-age clusters, with ages in the range 15 Myr to 1.5 Gyr, the median cluster diameter is found to increase with age. Small, compact clusters are rare among objects with ages >1.5 Gyr. Open clusters with ages >1 Gyr appear to form what might be termed a "cluster thick disk," part of which consists of objects that were probably captured gravitationally by the main body of the Galaxy.

Key word: open clusters and associations: general

Online material: machine-readable table

1. INTRODUCTION

Star clusters may be classified on the basis of three objective parameters: mass, age, and size (Whitmore 2004). These parameters are now available for the majority of Galactic globular clusters (e.g., van den Bergh & Mackey 2004; Mackey & van den Bergh 2005) and for some of the globular clusters in nearby galaxies that are members of the Local Group. However, such basic information is still lacking for the majority of Galactic open star clusters.

For very early discussions of Galactic open clusters and compilations of data on these objects, the reader is refereed to ten Bruggencate (1927) and Sawyer-Hogg (1959). More recently, Lyngå (1987) has published an updated catalog of data on open clusters. Using this information, Janes et al. (1988) discussed some of the general properties of the Galactic open cluster system. A much more detailed compilation of data on Galactic open clusters has recently been published by Dias et al. (2002). A version of this catalog (Dias & Lépine 2005) that had been updated to 2005 March was used for our investigation. A statistical discussion of some of this material has very recently been published by Bonatto et al. (2006). It is the purpose of the current investigation to assemble all currently available data on those Galactic clusters for which linear diameters could be calculated from the published data. It is hoped that the (often only fragmentary) information that is currently available might provide some useful constraints on the evolutionary history of the system of Galactic open clusters, or perhaps even on that of the Milky Way itself. In particular, it is hoped that the large number of open clusters for which diameters are now available can, at least in a statistical sense, compensate for the relatively low quality of some of the published data on individual Galactic star clusters.

2. THE CATALOG

The data by Dias & Lépine (2005) were used to compile Table 1. Only those clusters for which the data allowed the calculation of the cluster diameter are included in this table. For each cluster the following information is listed: (1) a cluster running number, (2) the cluster name, (3) the truncated Galactic longitude, (4) the cluster diameter in parsecs, (5) the distance from the Sun to the cluster in parsecs, (6) the distance of the cluster from the Galactic plane calculated by assuming that $z = R \sin b$, (7) the reddening $E(B - V)$ of the cluster as determined from photoelectric photometry, and (8) the logarithm of the cluster age in years, as derived from its dereddened color-magnitude diagram. Perchance, the total number of clusters in the database for which linear diameters could be determined was exactly 600. A recent study by Joshi (2005) suggests that the present cluster data are probably more or less complete out to a distance of 2 or 3 kpc.

3. DISCUSSION

3.1. *Dependence on Galactic Longitude*

The longitude distribution of the open clusters listed in Table 1 is plotted in Figure 1. This distribution is seen to exhibit maxima in the regions of active star formation at $l \sim 125°$ (Cassiopeia), $l \sim 205°$ (Monoceros), $l \sim 240°$ (Canis Major), and $l \sim 285°$ (Carina). The deepest minimum occurs in the obscured region at $l \sim 50°$ (Sagitta). The distribution of clusters in Galactic longitude depends on age (Dias & Lépine 2005). The present data show that the youngest star clusters with ages $<1 \times 10^7$ yr are strongly concentrated in the Carina arm ($280° < l < 300°$) and along the Sagittarius arm ($l = 330°$–$20°$). On the other hand, the oldest open clusters with ages $>1 \times 10^9$ yr clearly favor the region with $190° < l < 260°$. Possible contributors to this excess of very old clusters in the zone from $l \sim 190°$ to $\sim 260°$ are (1) relatively low Galactic absorption, (2) the fact that destructive tidal forces exerted by giant molecular clouds are smallest in the Galactic anticenter direction (van den Bergh & McClure 1980), and (3) the possible presence of a number of clusters that may be associated with the Canis Major dwarf galaxy (e.g., Bellazzini et al. 2006) rather than with the Milky Way system itself. According to Bellazzini et al., the following clusters in Table 1 are possibly associated with the CMa system: Tombaugh 2, Arp-Madore 2, NGC 2243, Melotte 66, van den Bergh–Hagen 66, and Sauer 2. All of these objects, except vdB-H 66 (for which log $T = 8.9$), have ages greater than 1.0 Gyr. It is not yet clear to what extent the overdensity of old clusters having ($190° < l < 260°$) is due to the putative Monoceros Ring in the background of the Canis Major dwarf galaxy (Conn et al. 2005), or

<div style="text-align:center">

TABLE 1
DIAMETERS OF OPEN CLUSTERS

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Number (1)	Name (2)	l (deg) (3)	D (pc) (4)	R (pc) (5)	Z (pc) (6)	$E(B-V)$ (7)	$\log T$ (8)
001............	Trumpler 31	002	1.43	986	−0039	0.35	8.87
002............	N6520	002	2.29	1577	−0078	0.43	7.72
003............	N6530	006	5.42	1330	−0031	0.33	6.87
004............	Bochum 14	006	0.34	578	−0005	1.51	7.00
005............	N6514	007	6.65	816	−0004	0.19	7.37

NOTE.—Table 1 is published in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

perhaps to the "Galactic Anticenter Structure" discussed by Frinchaboy et al. (2004, 2006) and Martin et al. (2005).

3.2. *Distribution of Cluster Diameters*

The distribution of the diameters of the open clusters that are listed in Table 1 shows a peak at $D \sim 2.6$ pc, with half of all clusters having $D < 3.5$ pc. The distribution of the diameters of clusters having different ages is plotted in Figure 2 and listed in Table 2. The distribution of diameters of young clusters with ages <15 Myr (Fig. 2a) shows a much broader wing toward large radii than does the distribution of intermediate-age clusters having ages in the range 15–150 Myr (Fig. 2b). A Kolmogorov-Smirnov (K-S) test shows that there is only a 0.3% probability that these two distributions were drawn from the same parent population. As previously noted by Janes et al. (1988; see their Fig. 3), the reason for the broad wing in the diameter distribution of young "clusters" is probably that many of the listed objects with large radii are actually positive-energy expanding associations (Ambartsumian 1954; Blaauw 1964) rather than negative-energy bound clusters. Of the young clusters with ages $T < 15$ Myr listed in Table 2, 29% have $D > 7.0$ pc, compared to only 9% of the clusters with ages in the range 15 Myr $< T <$ 150 Myr. This suggests that $\sim$20% of the young "clusters" listed in Table 1 are actually expanding associations with $D >$ 7.0 pc rather than stable clusters. Since very young associations might not yet have had time to expand to $D = 7.0$ pc, the total fraction of positive-energy systems in the present data sample must actually be even greater than 20%.

A comparison between the diameter distributions of intermediate-age clusters with ages in the range 15–150 Myr (Fig. 2b) and older clusters with ages of 150 Myr to 1.5 Gyr (Fig. 2c) shows that the older clusters are systematically larger than the intermediate-age clusters. A K-S test shows that there is only a 0.6% probability that these two distributions were drawn from the same parent population. Intermediate-age clusters are seen to have a peak in their diameter distribution at $D \sim 2.0$ pc, compared to a peak diameter of $D \sim 3.0$ pc for the older clusters. Possibly this increase in cluster diameter with age (which was also found by Bonatto et al. 2006) is, at least in part, due to the loss of gas by evolving stars (Schweizer 2004). Finally, Figure 2d shows that the most ancient open clusters, with ages >1.5 Gyr, are systematically larger than the clusters that have ages in the range 150 Myr to 1.5 Gyr. A K-S test shows that there is only a 0.3% probability that the open clusters with ages 150 Myr to 1.5 Gyr and those with ages >1.5 Gyr were drawn from the same parent population. This result is somewhat counterintuitive, because one might have expected the most tightly bound clusters to sur-
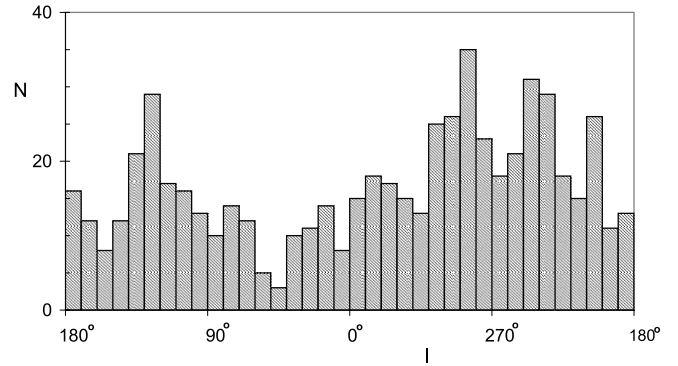

FIG. 1.—Distribution of Galactic clusters in longitude, exhibiting maxima in regions of active star formation at $l \sim 125°$ (Cassiopeia), $l \sim 205°$ (Monoceros), $l \sim 240°$ (Canis Major), and $l \sim 285°$ (Carina). The deepest minimum occurs near the obscured region at $l \sim 50°$ (Sagitta).

vive longest. This effect is, at least in part, due to the fact that the oldest clusters tend to be located in the Galactic anticenter direction.

3.3. *Cluster Diameter and Galactocentric Distance*

Many years ago van den Bergh & Morbey (1984) showed that the half-light radii of globular clusters grow significantly with increasing galactocentric distance. This raises the question of whether a similar relation exists between the radii and the galactocentric distances of open clusters. Unfortunately, it turns out that this question cannot yet be answered unambiguously with the present data. The reason for this is that the apparent cluster radii listed in Table 1 are affected by the stellar background density on which a cluster is projected. In the direction of the Galactic center ($l = 320°–40°$), low-latitude clusters with $| b | < 2°.0$ (which are projected on high-density star fields) are seen to appear significantly smaller than the clusters with $| b | > 2°.0$ that appear projected on lower density star fields. A similar effect is observed in the anticenter direction ($140° < l < 220°$), where open clusters with $| b | < 0°.6$ are seen to be significantly smaller than those that occur at higher latitudes. As a result of this selection effect, which depends on stellar background (or foreground) density, it is not yet clear whether the observed increase in mean cluster diameter with galactocentric radius is intrinsic or is (at least in part) due to observational selection effects. Such selection effects could be greatly reduced (or eliminated) by measuring the half-light radii R_h of a significant number of Galactic open clusters. With such data on cluster R_h values it should be possible to establish beyond reasonable doubt whether remote open clusters are systematically larger than those that occur closer to the Galactic center. Such an effect might be expected because disruptive tidal forces are smallest at large galactocentric radii. Furthermore, clusters at large galactocentric distances are less likely to be destroyed by interactions with giant molecular clouds (van den Bergh & McClure 1980).

There is a possible inherent problem with the present data that results from the fact that unusually rich clusters, such as NGC 6791 ($D = 17$ pc) and NGC 7789 ($D = 17$ pc), may have been traced to large radii as a result of their huge stellar population rather than because of an intrinsically large half-light radius. Clearly, it would be important to measure the half-light radii of Galactic open clusters so as to avoid this type of bias for the cluster radii that have been published in the literature. Finally, the diameters derived from a *Hipparcos* proper-motion search for
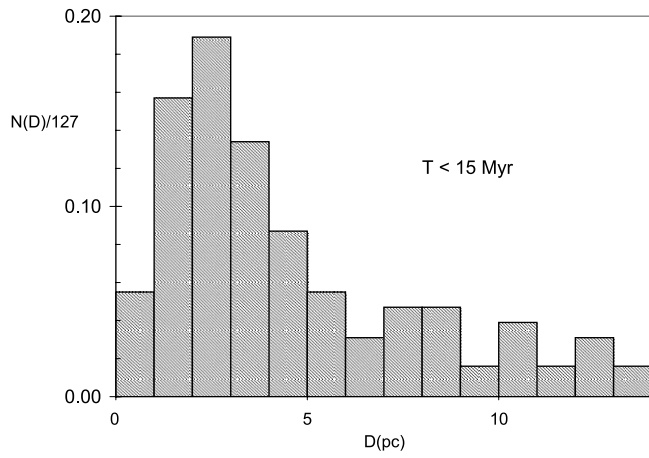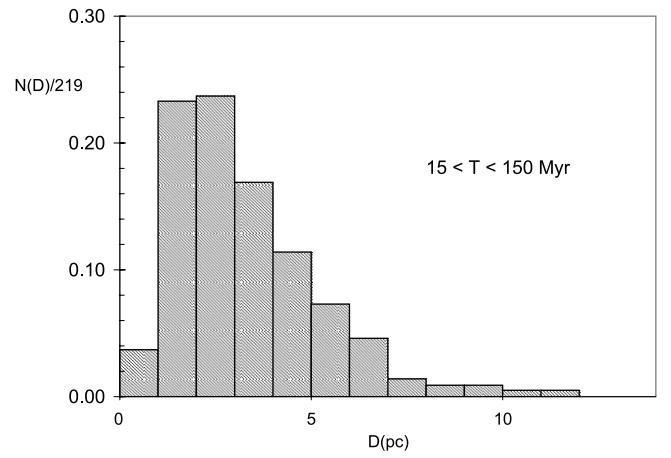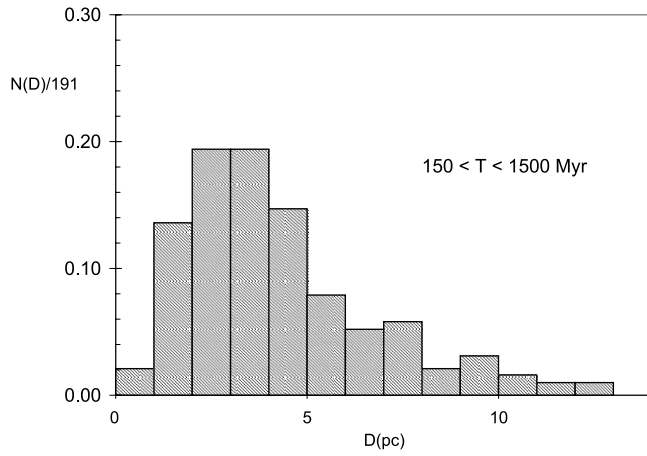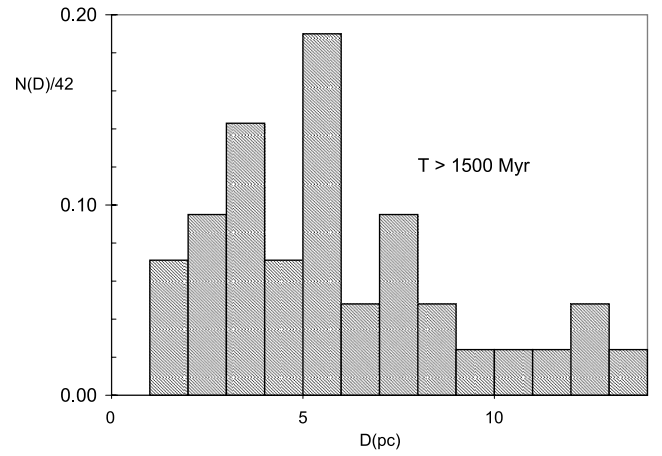
Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

Fig. 2.—Relation between the age and diameter of clusters. The figures appear to show the following: (1) The median cluster diameter grows with increasing age. (2) Compact clusters are rare among very old clusters with ages >1.5 Gyr. Finally, (3) the youngest objects with ages <15 Myr are probably a mixture of compact bound clusters and diffuse expanding associations.

TABLE 2
NORMALIZED FREQUENCY DISTRIBUTION OF GALACTIC CLUSTER DIAMETERS AS A FUNCTION OF CLUSTER AGE T

D (pc)	$T < 15$ Myr [$N(D)/127$]	15 Myr $< T < 150$ Myr [$N(D)/219$]	0.15 Gyr $< T < 1.5$ Gyr [$N(D)/191$]	$T > 1.5$ Gyr [$N(D)/42$]
0.5........................	0.055	0.037	0.021	0.000
1.5........................	0.157	0.233	0.136	0.071
2.5........................	0.189	0.237	0.194	0.095
3.5........................	0.134	0.169	0.194	0.143
4.5........................	0.087	0.114	0.147	0.071
5.5........................	0.055	0.073	0.079	0.190
6.5........................	0.031	0.046	0.052	0.048
7.5........................	0.047	0.014	0.058	0.095
8.5........................	0.047	0.009	0.021	0.048
9.5........................	0.016	0.009	0.031	0.024
10.5......................	0.039	0.005	0.016	0.024
11.5......................	0.016	0.005	0.010	0.024
12.5......................	0.031	0.000	0.010	0.048
13.5......................	0.016	0.000	0.000	0.024
14.5......................	0.016	0.009	0.005	0.000
>15	0.063	0.041	0.026	0.095

TABLE 3
DISTRIBUTION OF THE VALUES OF $\log|z|$ IN TABLE 1

$\log|z|$	$n(\log|z|)$	$\log|z|$	$n(\log|z|)$
<0.0	3	1.8–<2.0	85
0.0–<0.2	5	2.0–<2.2	65
0.2–<0.4	11	2.2–<2.4	36
0.4–<0.6	10	2.4–<2.6	26
0.6–<0.8	13	2.6–<2.8	16
0.8–<1.0	29	2.8–<3.0	9
1.0–<1.2	43	3.0–<3.2	10
1.2–<1.4	71	3.2–<3.4	3
1.4–<1.6	81	≥3.4	0
1.6–<1.8	84	. . .	. . .

clusters and associations by Platais et al. (1998) are almost all unusually large.

3.4. Distribution of Cluster Distances from the Galactic Plane

The data in Table 3, which are plotted in Figure 3, show that the open clusters in Table 1 are strongly concentrated toward the Galactic plane, with half of all clusters having $|z| < 48$ pc. Some caution should, however, be used in analyzing and interpreting such data because (Joshi 2005; Reed 2005) the frequency of nearby open clusters appears to peak at $z \sim -25$ pc. It is not immediately clear how much of this offset is due to a displacement of the local dust layer from the Galactic plane, the location of the Sun above the Galactic plane, and/or an asymmetry in the distribution of young star formation near the Sun with respect to the Galactic plane. The distribution of Galactic open clusters in $|z|$ exhibits a broad tail containing 13 objects (see Table 4) that are located at more than 1.0 kpc from the Galactic plane. It is of interest to note that all such objects for which it has been possible to derive ages from color-magnitude diagrams are older than 1×10^9 yr. Perhaps the most famous example of such very old clusters at high $|z|$ is the metal-rich open cluster NGC 6791 (Stetson et al. 2003; King et al. 2005), which is situated at $z = +1.1$ kpc. It is of particular interest to note that 4 of the 13 objects in Table 4 that are situated far from the Galactic plane appear to be associated with the Canis Major dwarf system. This suggests that captured dwarf galaxies may have provided a significant contribution to the population of open clusters with $|z| > 1$ kpc. One might perhaps think of such open clusters far from the Galactic plane as constituting a kind
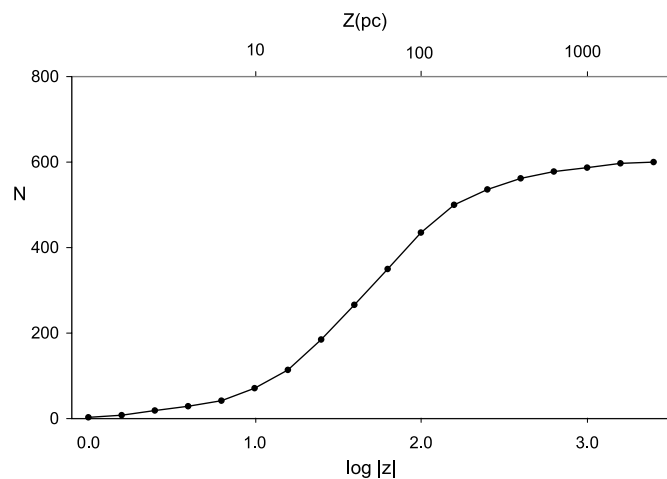

Z(pc)

FIG. 3.—Integral distribution of $\log|z|$ values for Galactic open clusters.

TABLE 4
OPEN CLUSTERS LOCATED >1.0 kpc FROM THE GALACTIC PLANE

Name	z	$\log T$
NGC 6791	+1107	9.64
NGC 7772	−1047	9.17
Berkeley 29	+2076	9.02
NGC 2420	+1036	9.05
Berkeley 22	−1073	9.03
Berkeley 20	−2494	9.78
Sauer 1	+1425	9.85
Tombaugh 2	−1588	9.01[a]
NGC 2243	−1379	9.03[a]
Arp-Madore 2	−1366	9.34[a]
Melotte 66	−1061	9.44[a]
ESO 092-18	−1229	9.02
van den Bergh–Hagen 176	+1008	9.08[b]

[a] Probably associated with the Canis Major dwarf.
[b] Age from Frinchaboy et al. (2006).

of "thick disk" (see Dalcanton et al. 2006), i.e., a population that has (at least in part) been derived from the tidal capture of initially extragalactic objects. The data in Table 1 clearly show that the oldest clusters are situated at greater distances from the Galactic plane than are the more recently formed clusters. Of the 44 clusters with ages >1.5 Gyr, half are located at $|z| < 278$ pc, compared to half having $|z| < 48$ pc for the entire cluster sample. This large difference is, no doubt, due to both (1) the preferential destruction of old clusters close to the Galactic plane by giant molecular clouds and disk shocks and (2) the fact that the oldest open cluster sample is more enriched in objects that were gravitationally captured by the Galaxy.

It is also noted that the vast majority of clusters located toward the Galactic center ($l = 320°-40°$) have $|z| < 100$ pc, whereas most of the clusters in the anticenter direction ($140° < l < 220°$) are situated at $|z| > 100$ pc.

3.5. Distribution of Reddening Values

The distribution of reddening values for the clusters in Table 1 is listed in Table 5. The observed cluster reddenings range from quite low values for nearby clusters and objects at high Galactic latitudes to $E(B-V) = 2.25$ and 3.00 for the highly obscured low-latitude clusters van den Bergh–Hagen 245 and Westerlund 1, respectively. Only ∼2% of the clusters in the present sample have $E(B-V) > 1.50$. Most of these highly reddened clusters are situated within 30° of the Galactic center. On the other hand, the majority of the slightly reddened clusters are located toward the Galactic anticenter. A detailed discussion of the distribution

TABLE 5
DISTRIBUTION OF CLUSTER REDDENING
VALUES $E(B-V)$

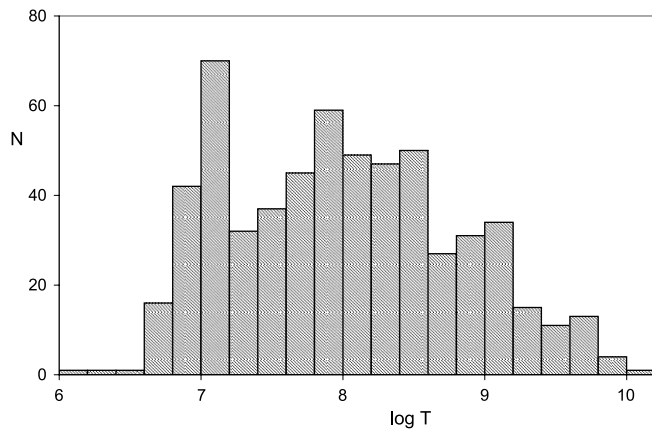| $E(B-V)$	N
0.00–0.19	145
0.20–0.39	143
0.40–0.59	141
0.60–0.79	75
0.80–0.99	36
1.00–1.19	16
1.20–1.39	17
1.40–1.59	5
≥160	9
?	13

Fig. 4.—Distribution of cluster ages. This figure shows a broad maximum centered at $\log T \sim 8.0$ and a narrower peak at $\log T \sim 7.1$.

TABLE 6
DISTRIBUTION OF CLUSTER AGES

log T (yr)	N	log T (yr)	N
6.00–6.19	1	8.20–8.39	47
6.20–6.39	1	8.40–8.59	50
6.40–6.59	1	8.60–8.79	27
6.60–6.79	16	8.80–8.79	31
6.80–6.99	42	9.00–9.19	34
7.00–7.19	70	9.20–9.39	15
7.20–7.39	32	9.40–9.59	11
7.40–7.59	37	9.60–9.79	13
7.60–7.79	45	9.80–9.99	4
7.80–7.99	59	10.00–10.19	1
8.00–8.19	49	. . .	. . .

of reddening values from a slightly larger sample of 722 clusters (which did not all meet the requirement that they have published diameters) has recently been given by Joshi (2005). His reddening map appears to show evidence for an $\sim$4 kpc long dust arm that comes as close as $\sim$1.5 kpc at $l \sim 40°$.

3.6. *Distribution of Cluster Ages*

Ages are available for 586 of the open clusters listed in Table 1. These clusters are found to have ages that range from 1×10^6 yr (NGC 6618) to 1.2×10^{10} yr (Berkeley 17). The distribution of observed open cluster ages is given in Table 6 and shown in Figure 4. These data and those for the slightly larger sample of Joshi (2005) both exhibit a broad age maximum centered at $\log T \sim 8.0$ on which a much narrower subsidiary peak at $\log T = 7.1$ (12 million years) appears to be superposed. This narrow age peak seems to be mainly associated with groupings of young clusters at longitudes $120°–140°$, $230°–250°$, and $280°–300°$. The observed peak at $\log T \sim 8.0$ is in good agreement with theoretical expectations (Wielen 1971).

4. DESIDERATA

For a variety of reasons, far less structural information is available on Galactic open clusters than is the case for Galactic globular clusters. It would be particularly valuable to obtain a homogeneous set of half-light diameters for a large sample of open clusters to see how this parameter depends on age, galactocentric distance, etc. Furthermore, it might be interesting to look for possible Galactic progenitors to objects like the "faint fuzzies" of Larsen & Brodie (2000). Due to heavy contamination by disk stars it would be particularly important to use two-color photometry to filter out field stars before attempting to measure such cluster half-light

radii. A telescope of only moderate aperture would be required to make these important measurements. It would also be important to obtain homogeneous photometric data on the integrated photometric properties of a representative sample of Galactic open clusters.

5. CONCLUSIONS

It is confirmed that young "clusters" with ages <15 Myr contain a significant subpopulation of objects with diameters >7 pc. The majority of these large structures are, as was previously noted by Janes et al. (1988), probably positive-energy expanding associations rather than stable negative-energy star clusters. Over the age range from 15 Myr to 1.5 Gyr, the diameters of clusters are found to increase with age. Small, compact clusters are conspicuously absent among the oldest objects, with ages >1.5 Gyr. The radii of open clusters in the direction of the Galactic center appear to be significantly smaller than those of clusters seen in the anticenter direction. In this respect open clusters resemble globular clusters, which are well known to be biggest at large galactocentric distances. This apparent dependence of cluster radius on galactocentric distance might be caused by (1) the preferential destruction of large clusters by disk/bulge shocks at small values of R_{gc}, (2) the paucity of destructive interactions with giant molecular clouds at large values of R_{gc}, and (3) observational selection effects resulting from the high stellar background density toward the Galactic center.

REFERENCES

Ambartsumian, V. A. 1954, Trans. IAU, 8, 665
Bellazzini, M., Ibata, R., Martin, N., Lewis, G. F., Conn, B., & Irwin, M. J. 2006, MNRAS, 366, 865
Blaauw, A. 1964, ARA&A, 2, 213
Bonatto, C., Kerber, L. O., Bica, E., & Santiago, B. X. 2006, A&A, 446, 121
Conn, B. C., Martin, N. F., Lewis, G. F., Ibata, R. A., Bellazzini, M., & Irwin, M. J. 2005, MNRAS, 362, 475
Dalcanton, J. J., Seth, A., & Yoachim, P. 2006, in Island Universes: Structure and Evolution of Disk Galaxies, ed. R. De Jong (Berlin: Springer), in press (astro-ph/0509700)
Dias, W. S., Alessi, B. S., Moitinho, A., & Lépine, J. R. D. 2002, A&A, 389, 871
Dias, W. S., & Lépine, J. R. D. 2005, ApJ, 629, 825
Frinchaboy, P. M., Majewski, S. R., Crane, J. D., Reid, I. N., Rocha-Pinto, H. J., Phelps, R. L., Patterson, R. J., & Munoz, R. R. 2004, ApJ, 602, L21

Frinchaboy, P. M., Munoz, R. R., Phelps, R. L., Majewski, S. M., & Kunkel, W. E. 2006, AJ, 131, 922
Janes, K. A., Tilley, C., & Lyngå, G. 1988, AJ, 95, 771
Joshi, Y. C. 2005, MNRAS, 362, 1259
King, I. R., Bedin, L. R., Piotto, G., Cassisi, S., & Anderson, J. 2005, AJ, 130, 626
Larsen, S. S., & Brodie, J. P. 2000, AJ, 120, 2938
Lyngå, G. 1987, Computer Based Catalogue of Open Cluster Data (5th ed.; Strasbourg: CDS)
Mackey, A. D., & van den Bergh, S. 2005, MNRAS, 360, 631
Martin, N. F., Ibata, R. A., Conn, B. C., Lewis, G. F., Bellazzini, M., & Irwin, M. J. 2005, MNRAS, 362, 906
Platais, I., Kozhurina-Platais, V., & van Leeuwen, F. 1998, AJ, 116, 2423
Reed, B. C. 2005, J. R. Astron. Soc. Canada, submitted (astro-ph/0507655)

Sawyer Hogg, H. 1959, Handb. Phys., 53, 129

Schweizer, F. 2004, in ASP Conf. Ser. 322, The Formation and Evolution of Massive Young Star Clusters, ed. H. J. G. L. M. Lamers, L. J. Smith, & A. Nota (San Francisco: ASP), 111

Stetson, P. B., Bruntt, H., & Grundahl, F. 2003, PASP, 115, 413

ten Bruggencate, P. 1927, Sternhaufen (Berlin: Springer)

van den Bergh, S., & Mackey, A. D. 2004, MNRAS, 354, 713

van den Bergh, S., & McClure, R. D. 1980, A&A, 88, 360

van den Bergh, S., & Morbey, C. L. 1984, Astron. Express, 1, 1

Whitmore, B. C. 2004, in ASP Conf. Ser. 322, The Formation and Evolution of Massive Young Star Clusters, ed. H. J. G. L. M. Lamers, L. J. Smith, & A. Nota (San Francisco: ASP), 419

Wielen, R. 1971, A&A, 13, 309