Morphology of Galactic Open Clusters

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ABSTRACT

We analyzed the shapes of 31 Galactic open clusters by star counting analysis of the 2MASS star catalog database. Morphological parameters such as the ellipticity and size have been derived via stellar density distribution, weighed by clustering probability. We find that most star clusters are elongated, even for the youngest star clusters of a few million years old, for which the structure must reflect the conditions in the parental molecular clouds and during the cluster formation, rather than as the result of stellar dynamics. We also find that the ellipticity a star cluster is correlated with the height of the cluster above the Galactic disk, suggesting prominent influence of the Galactic tidal force. We discuss how internal relaxation process is competing with Galactic external perturbation during cluster evolution.

Subject headings: stellar dynamics; methods: data analysis; galaxies: star clusters

1. Morphology of Star Clusters

The way member stars distribute within a star cluster changes as the cluster evolves. The *initial* stellar distribution is governed by the structure of the parental molecular cloud, and by how star formation proceeds. Sequential star formation, for example, may result in massive stars, which are responsible for inducing the formation of next-generation stars, having a birth place markedly different from that of low-mass stars. As the star cluster evolves, the distribution is modified by *internal* gravitational interaction among member stars. Subsequently stellar evaporation and *external* disturbances — e.g., Galactic tidal force, differential rotation, and encounters with molecular clouds — would alter the spatial structure and eventually dissolve the cluster. While individual star clusters are good laboratories to study stellar dynamics (Friel 1995), they also serve as test particles to probe the local physical (e.g., gravitational field) and chemical (e.g., metallicity) conditions. Open clusters in particular, with their wide ranges of age and location distribution, would be valuable tools to study the star formation history and chemical evolution of the Galactic disk.

Stars in a globular cluster are known to concentrate progressively toward the center, more so for massive stars than for low-mass stars. The density distribution, prescribed by the King model (King 1966), is understood as a combination of an isothermal sphere (i.e., dynamically relaxed) in the inner part of the cluster, and tidal truncation by the Milky Way in the outer part. In contrast, open clusters appear irregularly shaped, with member stars sparsely distributed. The youngest clusters must still bear the imprint of their formation history, so their structure, when compared with that of molecular clouds, may shed crucial light to the fragmentation process during cloud collapse. At the other end, the oldest open clusters serve as tracers of the structural and evolutionary history of the Galactic disk (Friel 1995). Even though some open clusters are known to follow King model (King 1962), and despite some elaborative theoretical considerations on the dynamics of open clusters (e.g., Portegies Zwart et al. (2001)), few systematically observational studies have been done until recently (e.g., Pandey, Mahra, & Sagar (1990), Nilakshi et al. (2002)), perhaps due to the complexity of the problem arising from the small number of member stars, and the lack of comprehensive data of open clusters on large angular scales.

As early as almost a century ago, Jeans (1916) already considered the flattening effect of a moving cluster through a general gravitation field of stars. Oort (1979) noticed the uneven distribution of stars in Hyades by comparison of the numbers of stars in quadrants about the cluster's apparent center. He concluded that the cluster appeared flattened with an axial ratio of about 2 aligned with the Galactic plane. Bergond, Leon, & Guibert (2001) analyzed the surface star density in 3 open clusters by a star counting method and found elongated shapes parallel to the Galactic plane. Furthermore these authors employed wavelet transform to bring out possible tidal tails, presumably caused by the Galactic tidal field.

A comprehensive diagnosis of the spatial structure of open clusters appears elusive because they are loose systems with shallow gravitational potential, so internal relaxation has not had time to occur in the youngest systems, and likewise the structure and hence the morphology and shape would be vulnerable to complex external perturbation. We would like to learn if young clusters are mass segregated, and if so, to what extent this is due to dynamical relaxation, as opposed to the relics of the structure in the molecular cloud. To answer questions like this, it is desirable to study the spatial structure of the youngest star clusters, and see how it evolves as a cluster ages and moves in its Galactic orbit.

As a pilot study on how a star cluster shapes out of the molecular cloud, we (Chen & Chen 2002) investigated the radial star density profiles of 7 open clusters with ages ranging from a few million years to a few billion years, based on the 2MASS (Two-Micron All-Sky Survey) Second Increment Release star catalog. The infrared data enabled us to probe the distribution of member stars that are very young and still embeded in molecular clouds. Our study indicated that stars, regardless of their masses, tend to concentrate progressively toward the center of a cluster, and the degree of concentration is higher for luminous (presumably more massive, or as binary) stars than for fainter members. Such a segregation structure appears to exist in even the youngest star clusters for which dynamical relaxation has not had sufficient time to take place. The spatial distribution of member stars in the youngest star clusters is much relevant to the structure in the parental cloud out of which the cluster was formed, and to subsequent mass redistribution during star (cluster) formation process.

Nilakshi et al. (2002) analyzed the radial star density profiles of some 38 open clusters based on the U.S. Naval Observatory (USNO)-A v2.0 star catalog, which in turns was derived from the Digital Sky Survey (DSS) plates. Because no membership information is available, the extent, size, shape, or any spatial structure of any particular star cluster is estimated in a statistical sense against adjacent Galactic star fields. One of the advantages of working with a homogeneous sky-survey database, such as the 2MASS or USNO catalog, in addition to the convenient availability, is the extended angular coverage, to encompass not only the entirety of a cluster itself (core, envelope, or possible tails), but also sufficient field regions for comparison. A fair assessment of the stellar density fluctuations in the comparison fields is crucial in the star counting technique.

Parameterization of the spatial structure of an open cluster by its radial distribution obviously is not adequate, as already pointed out by Nilakshi et al. (2002). Many open clusters have highly irregular shapes, often even with no clear centers, so circular symmetry cannot be readily assumed. Dense molecular cloud cores are shaped on average as a prolate Gaussian with an intrinsic axis ratio of 0.54, as a part of an evolutionary sequence from filamentary molecular cloud complexes to roughly spherically condensed cores (Curry 2002). It is therefore desirable to represent the stellar distribution by a more sophisticated method than a one-dimensional analysis. This paper summarizes the result of our attempt to analyze the morphology of open clusters, and how it would evolve in Galactic environments.

We take a probabilistic approach to estimate the stellar surface density of stars in the 2MASS point source catalog, and represent a star cluster with an ellipsoid. This allows us to investigate not only the structure (concentration, segregation) but also the shape (elongation, orientation) of a cluster, and hence by a sample of clusters of different ages and environments, to delineate the morphological evolution influenced by Galactic dynamics. The 2MASS infrared data are free from much of interstellar extinction, and thus would reveal the true shape of a star cluster more readily than in optical bands. Some youngest star clusters may be seen only in infrared wavelengths (Lada & Lada 2003). We describe our 2MASS sample of open clusters in Section 2, and present the methodology to analyze the morphology of open clusters in Section 3. The results and discussions are summarized as the last section.

2. Data of Open Clusters

Dias et al. (2002) complied the latest catalog of open clusters, which updated the previous work of Lyngä (1987) and of Mermilliod[1]. New data on the radial velocity, proper motion and metallicity were added. Of the total of more than 1600 entries, about 38% have distance, age and color-excess determinations. We note that while such a compilation is useful for information access and target selection, one should exercise caution when deriving statistics from the dataset, because the catalog may be far from completion — some of the entries may not be bona fide stellar groups at all. Severe extinction by dust near the Galactic plane makes it difficult at wavelengths shortward of infrared to recover the true shape, or even its bare existence, of young star clusters, which as recent studies show may outnumber optically visible open clusters by a factor of an order (Lada & Lada 2003).

We selected among the first 800 entries in the Dias et al. (2002) catalog open clusters that have available distance and age determinations and have an angular size between $3'$and $40'$. The choice of the angular range, somewhat arbitrary, is a convenient compromise between spatial resolution and the practical limit of maximal data (1 degree field of view) readily downloadable from the 2MASS web interface. Among the open clusters for which the 2MASS Point Source Catalog of the Second Incremental Release data were available, we selected those rich in density enhancement (by eye) and with as complete data coverage as possible, i.e., no nearby bright stars so as to contaminate the field. A bright star causes unreliable astrometric and photometric determinations of neighboring stars, rendering an incomplete listing in the 2MASS database. Interpolation of stellar density is possible in most cases as long as the contamination is not overwhelming (e.g., too bright or too close within the cluster boundary.) In the study we report here, none of the sample suffers bright-star contamination, and 31 open clusters were selected in the morphological analysis.

We note that even though our sample is selected from only half of the catalog of Dias et al. (2002), i.e., roughly from RA $0^{\rm h}$ to $12^{\rm h}$, there are no additional, obvious selection effects in our star cluster sample. Figure 1 shows the pole-on and edge-on Galactic distributions of our sample of 31 star clusters. Clusters younger and older than 800 Myrs are marked differently. It is noted that the majority (29) of our sample are in the direction of Galactic anti-center, a consequence of our sample selection. It is seen that old open clusters have a larger average scale height above the

[1]http://obswww.unige.ch/webda

Galactic plane than young star clusters.

3. Methodology

3.1. Statistical Membership

In the absence of membership information on individual stars, we estimate the structure of a star cluster by a probabilistic star counting technique, i.e., the boundary, shape, size are all determined in a statistical sense. In essence, the degree of clustering of neighbors around any star gives a measure of the likelihood of that star being in a cluster environment. One defines for each individual star i the clustering parameter,

$$P_i = (N_t - N_f)/N_t = 1 - N_f/N_t, \tag{1}$$

for which N_t is the total number of neighboring stars within a specified angular size (a "neighborhood aperture" centering on the ith star) and N_f is the average number of field stars within the same aperture. The number of field stars can be estimated by $N_f = \Sigma_f \times \pi r_p^2$ where Σ_f is the surface number density of field stars, estimated in regions away from the apparent star cluster and r_p is the angular size of the neighborhood aperture.

We see that the clustering parameter P_i gives a measure of local enhancement of stellar density, whose value ranges from $P_i \sim 0$ in a field region (for which $N_t \sim N_f$) to $P_i \sim 1$ near a rich cluster ($N_t \gg N_t$). In other words, P_i behaves very much like a probability of cluster membership. Our probabilistic method to analyze membership in a star cluster is similar to that used by Danilov & Seleznev (1990).

Note that the choice of r_p should not be arbitrary. If r_p is too small, the uncertainty in P_i will be large due to small-number statistics. On the other hand, if r_p is too large, the intrinsic structure of the cluster will be smoothed out and detailed structure information is no longer available.

We describe below our procedure to select an appropriate aperture size r_p from the surface density of field stars Σ_f. As long as both r_p and Σ_f for a cluster are determined, we can estimate the membership probability for each star by Eq. 1.

3.2. Surface Density of Field Stars

The cluster membership probability defined above is based on a measure of enhancement of local stellar density compared to field stars. A fair estimate of the density of field stars therefore is prerequisite. For each cluster, we use regions away ($\gtrsim 20'$) from the central cluster to estimate the mean number density of field stars.

Since our analysis of the cluster parameters is based on the statistics (star density, aperture size) in the surrounding field regions, obviously a homogeneous distribution of field stars must be assumed in order for our technique to work. We note actually in almost every case we encountered, the distribution of field stars is *not* homogeneous, due to the general vertical stellar gradient of the Galactic disk. Figure 2 shows such an example for which a density gradient is seen in either the RA or the DEC projection, with the overall gradient vector pointing toward the Galactic disk, as expected. We also find that, not surprisingly, the density gradient is higher for a line of sight with a lower Galactic latitude. This kind of density gradient, though potentially useful for study of Galactic stellar populations, poses only negligible effect on our results, typically a few percents at most across the fields of our star clusters. We therefore do not take the effect into account in our analysis of the shape of a star cluster.

The surface number density of field stars Σ_f is computed by counting number of stars in a certain sky area. Due to the discrete nature of individual stars, even for a homogeneous star field, Σ_f would approach a constant only when the sampling sky area is large enough to include a sufficient number of stars. Otherwise, when the sampling size is smaller than about the average angular separation of stars, large fluctuations result. As the minimum, one would demand a sky area to have a signal-to-noise of $\sqrt{N_f} \gtrsim 3$ against Poisson fluctuations, or $N_f \gtrsim 10$ field stars, and set the optimal neighborhood aperture size r_p accordingly. We usually take an empirical $N_f \sim 50$ (i.e., $S/N \sim 7$) to determine r_p. In general r_p is on order of a few arcminutes.

3.3. Cluster Shape and Morphology

With each star now being represented by a membership probability, the surface density of cluster member stars is then the sum of the clustering parameter of every star within each sky-coordinate grid (with area ΔS); that is, the effective number density of member stars is,

$$\Sigma_s = \sum P_i/\Delta S \tag{2}$$

Obviously in field star regions, $\Sigma_s \sim 0$. The morphology of a cluster is prescribed by density contours, at both the one-third level of the maximal density ($\Sigma_{\rm max}/3$), and at the boundary, defined as where the density drops to 2–3 times the background fluctuations. In the extreme case, e.g., NGC 2567, for which the star cluster is very sparse, a mere 1-σ outer boundary is used. Effectively the inner and outer ellipses trace, respectively, the core and the halo (or the corona as termed by some researchers) of a star cluster. The density contours are least-squares fitted with ellipses to obtain the eccentricities of the inner and outer ellipses, ($e_{1/3}$, and $e_{\rm out}$, and the size (average of the semimajor and semiminor axes). Other parameters, such as the position angle of the ellipse can also be obtained. We illustrate in Fig. 3 examples of two clusters with different morphology, one of relatively round shape (NGC 2414) and the other of elongated shape (NGC 1893). These two clusters will be compared in details in the next section.

We list the results for individual clusters of our sample in Table 1, where the first column gives the name of the cluster, the second and third columns are the coordinate of the Sun and age of each star cluster, taken from Dias et al. (2002). Columns 6 to 11 are, respectively, the ellipticities and corresponding semimajor axes derived from the density contours of member stars. Table 1 also lists $e_{1/2}$, and $r_{1/2}$, the shape and size parameters for the ellipse at half maximum, i.e., even closer to center of a cluster than the 1/3 maximum. Comparison between the 1/2 maximum and 1/3 maximum would idealy be indicative of cluster concentration, though we would not draw any conclusions on this aspect based on the small sample reported in this paper.

4. Discussions & Conclusions

Two kinds of dynamical effects act on, and influence the morphology of, an open cluster. The first is internal interaction of two-body relaxation due to encounters among member stars. This tends to organize the stars to distribute in a spherical shape, ever denser toward the cluster center. At the same time, some low-mass members may gain enough kinetic energy through the encounters and get thrown out of the system (i.e., stellar "evaporation"). The other dynamical process is external interaction, including tidal force due to Galactic disk or giant molecular clouds, and differential rotation for a cluster located in the inner disk region. These disruptive effects tend to make a star cluster elongated in shape, with the outer part particularly vulnerable.

Tidal disturbance on a star cluster is stronger when closer to the Galactic disk plane. Fig. 5 shows the vertical distance Z from the Galactic disk versus the age of the open clusters in Dias et al. (2002) catalog, of which our sample, separately marked, is a subset. As can be seen, young open clusters tend to locate much nearer to the disk than older clusters, a consequence of the birth place and dynamical processes of open clusters (Tadross et al. 2002; Chen, Hou & Wang 2003). If open clusters are separated into two age groups, old and young, with the dividing age, somewhat arbitrary, of that of the Hyades, 0.8 Gyr (Phelps et al. 1994; Chen, Hou & Wang 2003), the scale heights are 354 pc (old) and 57 pc (young), respectively (Chen, Hou & Wang (2003), based on the data compiled by Dias et al. (2002)). Tadross (2003) include additional consideration of the galacto-distances of the clusters and the results support the previous assertion (Lyngä & Palous 1987) that old clusters seem to distribute at larger scale-heights in the outer parts of the Galaxy than in the inner parts. Obviously, only star clusters away from the inner disk regions—where the tidal force from giant molecular clouds plays a major disruptive role in the structure or even the existence of a star cluster—would have survived on Galactic dynamical time scales (Janes & Phelps 1994).

Comparison between the two open clusters in Fig. 3 is informative. NGC 2414 is relatively poorly studied, perhaps because of its paucity and small angular extent. Much of the literature about this open cluster can be traced back to the photometric measurements in Vogt & Moffat (1972), based on 10 member stars. In comparison, NGC 1893 is prominently stretched toward the disk plane, with ellipticities $\gtrsim 0.7$ throughout the entire cluster. The cluster is associated with bright nebulosity and dark clouds, but does not seem to show positional variation of color excess $EB-V$ across the cluster (Yadav & Sagar 2001). The extinction effect would certainly be even smaller in the 2MASS 2μm data. Its elonagated shape (or of two subgroups) thus should be intrinsic to the stellar distribution within the cluter, rather than caused by extinction variation.

These two clusters share some similarities, both being relatively young, log (age) ~ 7 yr, and close to the disk plane, with NGC 2414 at $\ell \sim 231^{\circ}$, $b \sim +2^{\circ}$, and NGC 1893 at $\ell \sim 174^{\circ}$, $b \sim -2^{\circ}$. They however contrast greatly in shape, size, and richness. NGC 2414 is round, small, and contains some 74 member stars within its derived radius $\sim 3'$. NGC 1893 on the other hand is oval, twice as large in angular extent, and encompasses 645 member stars. NGC 1893 therefore has a much stronger gravitational binding than NGC 2414 against external disruption. What we see now in NGC 2414 may well be the remnant cluster core.

Such a stripping off of cluster halos is not uncommon. For example, Berkeley 17 (= C0517+305), the oldest open cluster known (Salarism, Weiss, & Percival 2004), has a protrusion manifestly pointing toward the Galactic disk (Fig. 6), with a projected extent comparable to the cluster's radius, ~ 6–$7'$, or about 5 pc in projected length assuming a 2.7 kpc distance (Dias et al. 2002). The enhancement ("corona") has already been inferred from radial stellar density distribution, and from the color-magnitude diagram of stars away from the nominal cluster region (Kałużny 1994). Our analysis brings up clearly the tail and its geometry, and further hints on an associated antitail, which typifies tidal distortion.

The old, metal-poor, and large-height cluster NGC 2420 (Friel et al. 2002), serves as a good showcase for interplay between internal stellar dynamics and external disturbances. This cluster is nominally listed in Dias et al. (2002) to have an angular diameter of $5'$, at a distance of 3085 pc, and a logarithmic age in years of 9.048, apparently taken from WEBDA. We adopt this distance and those of other star clusters in our studies from the Dias et al. (2002) catalog as a homogeneous source of input data, but note that the cluster may be considerably closer, at 2.28 kpc (Janes & Phelps 1994). Errors in distance estimation — which often turn out to be quite significant — would not affect the shape determination, but obviously would influence the results of any statistical analysis. Using star counting on a Palomar Sky Survey plate, Leonard (1988) already noted a much larger extent, to at least $20'$, from the apparent center of NGC 2420. Our analysis of the 2MASS data shows a negligible gradient in the field star density toward NGC 2420 (Fig. 4). The cluster itself is determined to have an inner (1/3 maximum) and outer (3-σ sky) ellipses with eccentricities of $e_{1/3} \sim 0.45$, $e_{\rm out} \sim 0.73$, respectively. Average sizes of $r_{1/3} \sim 3\farcm1$ and $r_{\rm out} \sim 11\farcm1$ are adopted. For NGC 2420, an aperture size $r_p = 3\farcm6$ has been used to estimate the field star density, $\Sigma_f \sim 1.2 \pm 0.1$ arcmin^{-2}, from which the surface density of member stars is then derived according to Eq. 2. At the 2MASS limit of Ks=15.6 mag, by summing up all P_is (Eq. 1), there are a total of 468$\pm$22 stars. This is to be compared with 685$\pm$27 within a radius of $20'$(Leonard 1988) up to the completeness of photographic ~ 19.5 mag, which cover a larger sky area and deeper in stellar photometry than the 2MASS data we use. We may be witnessing the disintegrating process of the outer part of NGC 2420.

We show in Fig. 7 and Fig. 8 for our sample of open clusters the shape ellipticities of the core ($e_{1/3}$) and of the outer boundaries ($e_{\rm out}$) versus their ages and heights above the Galactic disk (Z). One sees that all open clusters in our sample are elongated in shape.

Globular clusters are known to have elliptical shapes (White & Shawl 1987), likely due mainly to their overall rotation, rather than to Galactic tidal interactions (King 1961; Meyan & Mayor 1986). Kontizas et al. (1990) compared globular clusters in Large and Small Magellanic Clouds, and found that in virtually all cases, the inner parts are more elliptical than the outer parts. This is understood as the diminishing effect of rotation from the inner to the outer parts of a globular cluster. These authors also found that the SMC globular clusters are more elliptical than those of the LMC, which in turn are more elliptical than those in our galaxy, and that the outer shapes are somewhat flatter for younger systems (Kontizas et al. 1991).

Open clusters are known also to have elongated shapes but the orientation of the flattening, however, cannot be accounted for by Galactic tides alone (Jefferys 1976). This may be because that a giant molecular cloud, local to a particular open cluster, plays a more influential role in shaping the cluster than a general Galactic disk potential (Danilov 1996). Our analysis shows that even the youngest open clusters (several Myrs old) have very elongated shapes, with ellipticities > 0.4. This is to be compared with the inferred mean intrinsic axis ratio of 0.54 for the observed shapes of molecular cloud cores (Curry 2002). Young star clusters hence appear by and large to have inherited the morphological structure in the prenatal molecular clouds. Because of the low volume stellar number density of an open cluster, internal dynamics never becomes dominant so as to sphericalize the system (Portegies Zwart et al. 2001), in contrast to the case in globular clusters.

Fig. 7 shows how the shapes of the cluster cores (diagnosed with $e_{1/3}$) and of the outer boundary (with $e_{\rm out}$) evolve with time. The number of our sample of open clusters is small (31), yet it is tantalizing to note that while the shape of the outer boundary remains unconstrained with age, the core tends to become circularized with age. The slope of $e_{1/3}$ versus log(age) is -0.07 ± 0.03. If the sample is further divided to two groups according to the height from the disk plane $|Z|$, by the median value ~ 170 pc, one sees clearly that the large-height group (denoted by solid circles in Fig. 7) evinces a noticable tendency (slope -0.015 ± 0.09 of rapid spheridalization both in the core and in the halo. Low-lying cluster remain elongated from birth to date, prominently so for the outer parts, the most vulnerable to disruption. The large ellipticities for young clusters are primarily inherited from cluster formation process, but after $\sim 10^8$ yr or so, internal stellar dynamics become effective in shaping the core of a cluster.

Fig. 8 presents the data in a different way, namely how the ellipticity varies with the height from the disk plane, for old (solid symbols) and young systems. The youngest star clusters close to the disk clearly manifest the most elongated shapes. Away from the disk ($Z \gtrsim 2$ kpc) there seems an indication of generally more spherical core shape (smaller $e_{1/3}$ among older systems, again as the result of the working of dynamical relaxation. The wide range of ellipticities of outer boundaries among large-height and old systems is also consistent with the notion of the important role played by environmental disruption.

This paper presents our first attempt to delineate the structural evolution as a tool to probe the mass distribution and perhaps the dynamical evolution of our Galaxy. Our sample is too small for firm statistical inference, but some conclusions seem secured. Our study indicates that the shape or morphological structure of a young open cluster is dictated by the initial conditions in the parental molecular cloud and, as the cluster evolves, by both the internal gravitational interaction and external tidal perturbations. Only the initially massive and compact star clusters would have strong enough self-gravitational binding to endure the continuing destructive effects, which intensify near the disk plane and toward the inner parts of the Galaxy. Statistics based on a larger sample of open clusters are obviously needed to quantify, e.g., the time scales, the intricate interplay of cluster evolution (age) and its Galactic location (galacto-centric distance, and height from the Galactic disk).

This work makes use of data products from the Two-Micron All-Sky Survey (2MASS), which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. CGS expresses his gratitude for the hospitality during his visit at NCU. WPC and CWC acknowledges financial support of the grant NSC92-2112-M-008-048 from National Science Council of Taiwan.

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Table 1. Morphological Parameters of Open Clusters

Name	(l, b)	d (pc)	Z (pc)	log age (yr)	$e_{\rm out}$	$e_{1/3}$	$e_{1/2}$	$r_{\rm out}$	$r_{1/3}$	$r_{1/2}$
NGC 2420	(198.11,+19.63)	3085	1036	9.05	0.48	0.34	0.22	11.60	3.72	2.73
NGC 2506	(230.56,+09.93)	3460	597	9.05	0.67	0.53	0.53	10.42	3.48	2.47
NGC 1893	(173.59,-01.68)	3280	-96	6.75	0.73	0.87	0.88	6.13	4.11	3.35
King 5	(143.74,-04.27)	1900	-141	9.00	0.82	0.61	0.74	4.86	2.65	2.04
NGC 6791	(69.96,+10.90)	5853	1107	9.64	0.60	0.41	0.23	8.60	3.90	2.99
Berkeley 17	(175.65,-03.65)	2700	-172	10.08	0.87	0.61	0.35	8.19	4.23	3.14
Mellote 71	(228.95,+04.50)	3154	247	8.37	0.87	0.47	0.45	10.13	3.83	2.57
NGC 1245	(146.65,-08.93)	2876	-446	8.70	0.65	0.19	0.38	10.21	4.40	3.39
Berkeley 69	(174.44,-01.79)	2860	-89	8.95	0.71	0.69	0.67	3.79	3.08	2.54
NGC 1960	(174.53,+01.07)	1318	25	7.47	0.73	0.64	0.59	7.60	5.65	4.27
King 8	(176.39,+03.12)	6403	348	8.62	0.63	0.69	0.43	2.54	1.69	1.17
Berkeley 21	(186.84,-02.51)	5000	-219	9.34	0.35	0.52	0.54	3.84	2.55	1.90
NGC 2414	(231.41,+01.95)	3455	118	6.98	0.45	0.45	0.47	3.14	2.81	2.33
Trumpler 7	(238.21,-03.33)	1474	-86	7.43	0.80	0.92	0.73	8.60	4.56	2.27
NGC 1907	(172.62,+00.31)	1556	8	8.57	0.48	0.65	0.62	4.19	3.33	2.02
NGC 2421	(236.27,+00.07)	2181	3	7.37	0.52	0.47	0.26	4.16	3.70	2.80
NGC 1817	(186.20,-13.10)	1972	-447	8.61	0.82	0.78	0.83	13.92	9.92	4.76
NGC 2567	(249.80,+02.96)	1677	87	8.47	0.83	0.58	0.35	7.51	4.02	3.14
Ruprecht 18	(239.93,-04.94)	1056	-91	7.65	0.68	0.63	0.77	6.84	6.29	4.58
NGC 2354	(238.37,-06.79)	4085	-483	8.13	0.70	0.64	0.77	3.35	1.95	1.55
Berkeley 39	(223.46,+10.09)	4780	837	9.90	0.57	0.28	0.50	7.76	3.55	2.67
NGC 2425	(231.50,+03.30)	4053	233	9.20	0.78	0.60	0.82	3.23	2.59	1.95
NGC 2383	(235.27,-02.46)	1655	-71	7.17	0.85	0.70	0.69	4.58	2.95	2.17
NGC 2355	(203.39,+11.80)	2200	450	8.85	0.49	0.61	0.71	7.47	4.04	3.01
NGC 2158	(186.63,+01.78)	5071	158	9.02	0.46	0.36	0.28	7.43	2.89	2.28
NGC2 194	(197.25,-02.35)	3781	-155	8.52	0.43	0.62	0.64	7.35	4.14	3.12
NGC 2204	(226.01,-16.11)	2629	-730	8.90	0.77	0.67	0.43	8.27	4.16	3.07
NGC 2304	(197.20,+08.90)	3991	617	8.90	0.56	0.47	0.49	3.16	2.20	1.97
Tombaugh 2	(232.83,-06.88)	13260	-1588	9.01	0.45	0.49	0.63	2.90	2.46	1.98
IC 348	(160.40,-17.72)	320	-97	6.80	0.85	0.43	0.56	8.53	3.87	3.03
NGC 1931	(173.90,+00.28)	3086	15	7.00	0.53	0.83	0.52	4.13	2.71	1.75

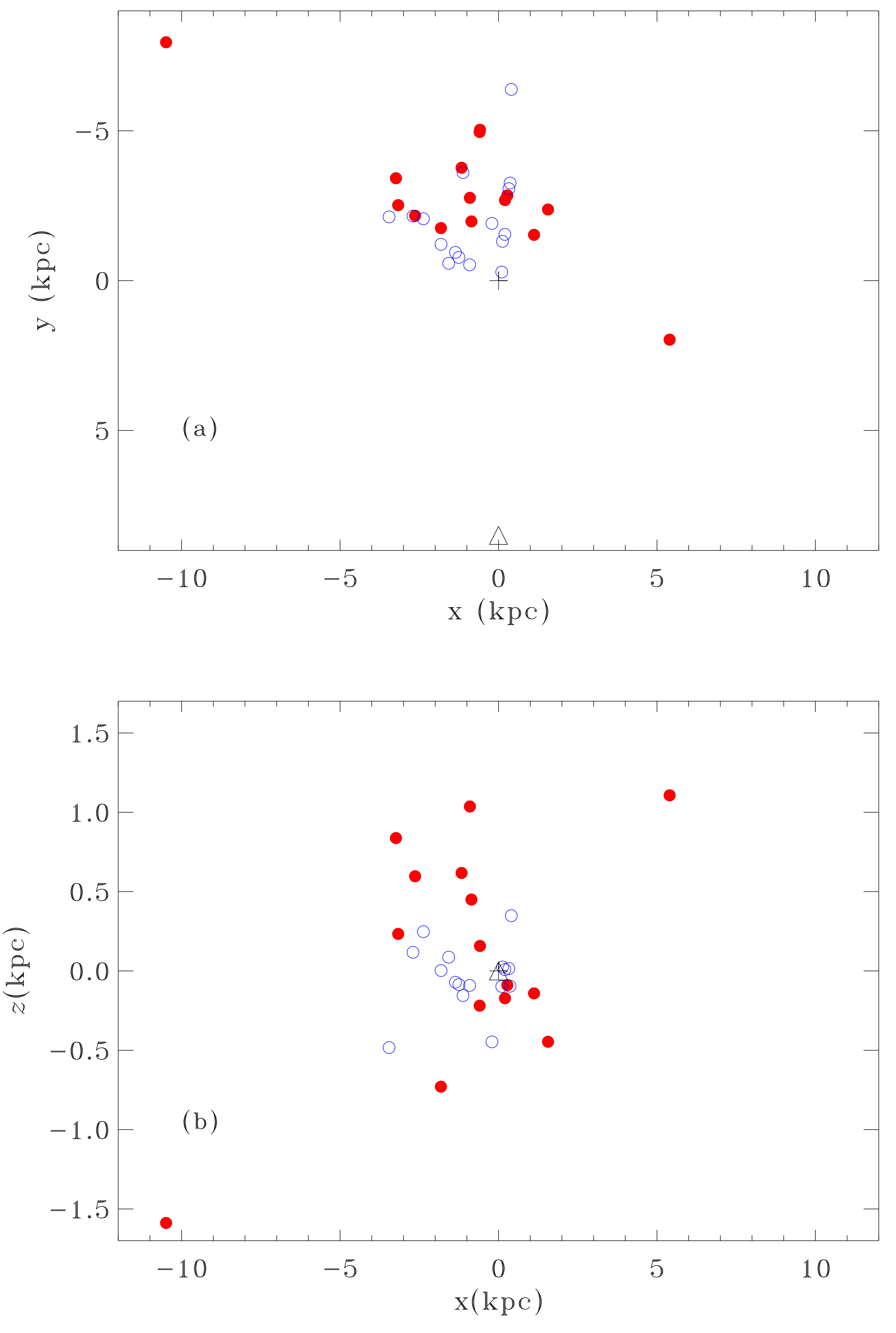

Fig. 1.— (a) Face-on view and (b) edge-on view of sample open clusters. The sun and Galactic center are marked. Young and old clusters (dividing by 800 Myrs) are denoted, respectively as open and filled circles. To the upper left near $(x, y) \approx (-10.5\ \mathrm{kpc}, -8\ \mathrm{kpc})$ is Tombaugh 2, which is among the most distant open clusters from the Galactic center and from the Galactic plane (Adler & Janes 1982). Located in the inner solar-circle near $(x, y) \approx (5.4\ \mathrm{kpc}, 2\ \mathrm{kpc})$ is NGC 6791, one of the oldest and most metal-rich open clusters (Chaboyer, Green & Liebert 1999; Friel et al. 2002). The edge-on view shows clearly that old open clusters occupy a wider range above and below the disk plane than young systems.

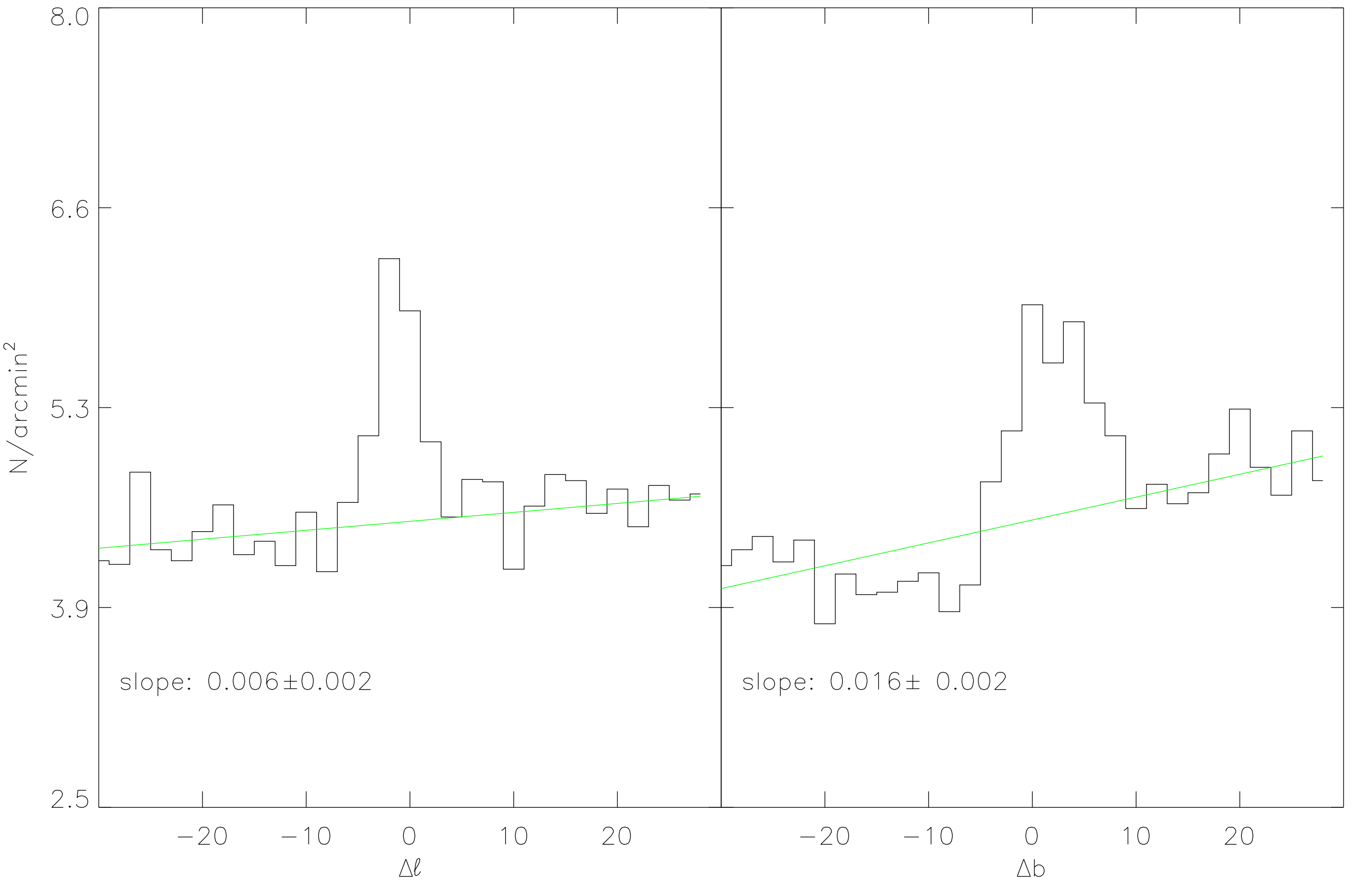

Fig. 2.— The number density of field stars exhibits gradients pointing toward the Galactic plane. In the example shown here for NGC 1893, the projected gradient across a 1 deg squared field is significantly smaller in the Galactic longitude than that along the latitude direction which amounts to ~ 2 sq. arcmin^{-2} per degree.

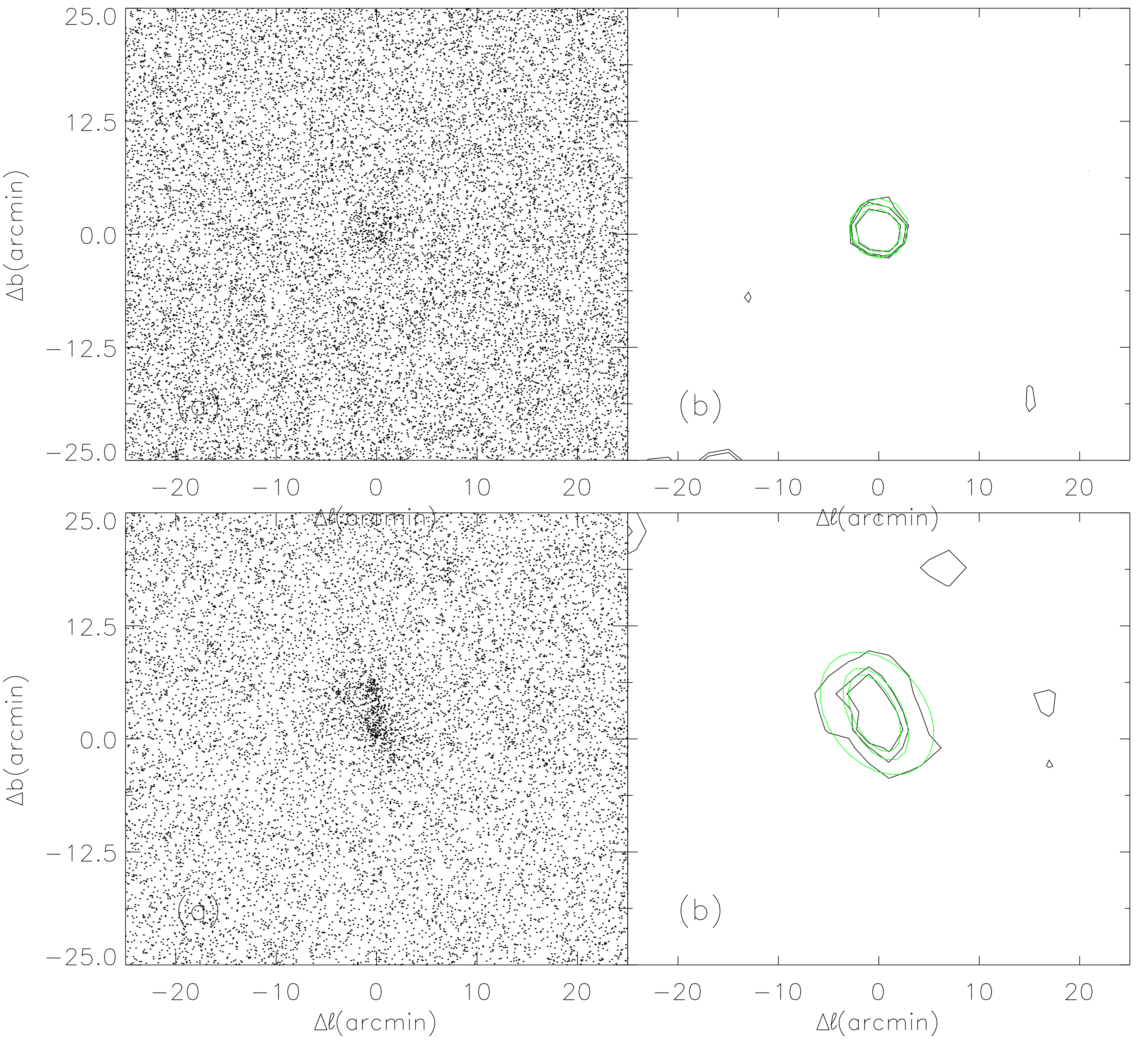

Fig. 3.— Examples of a spherically shaped open cluster, than 15.6 mag, the $\sim 3-\sigma$ limit at K_s band. The right panel plots the isodensity contours of cluster member stars, superimposed with the ellipses fitted to the 1/3 maximum number density and to the outer boundary of the cluster (see text.)

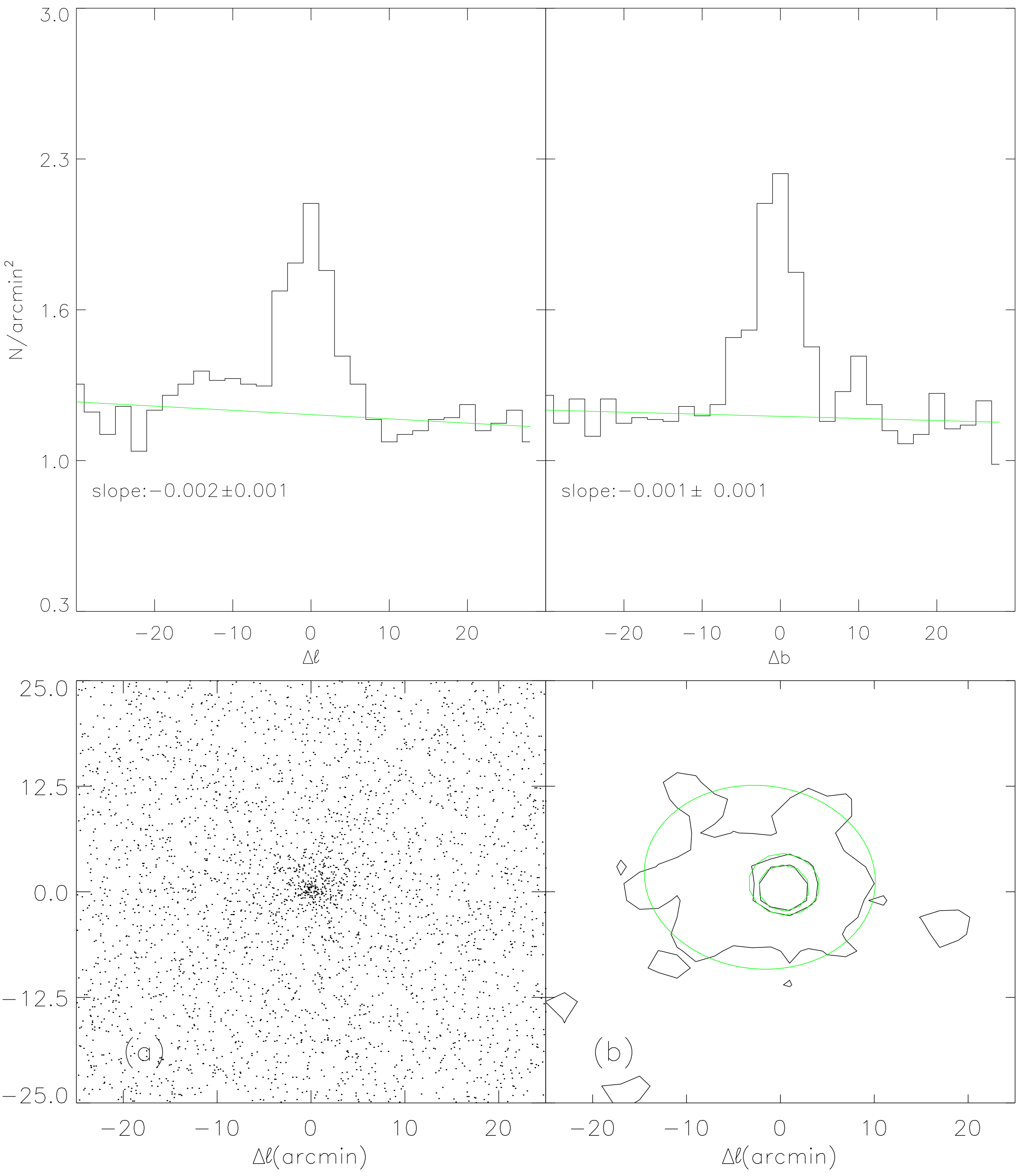

Fig. 4.— NGC 2420, being high above the Galactic plane, has a relatively uniform background stellar density in both the longitudinal and latitudinal directions. This old cluter has a rather spherical core and a loosely defined outer boundary.

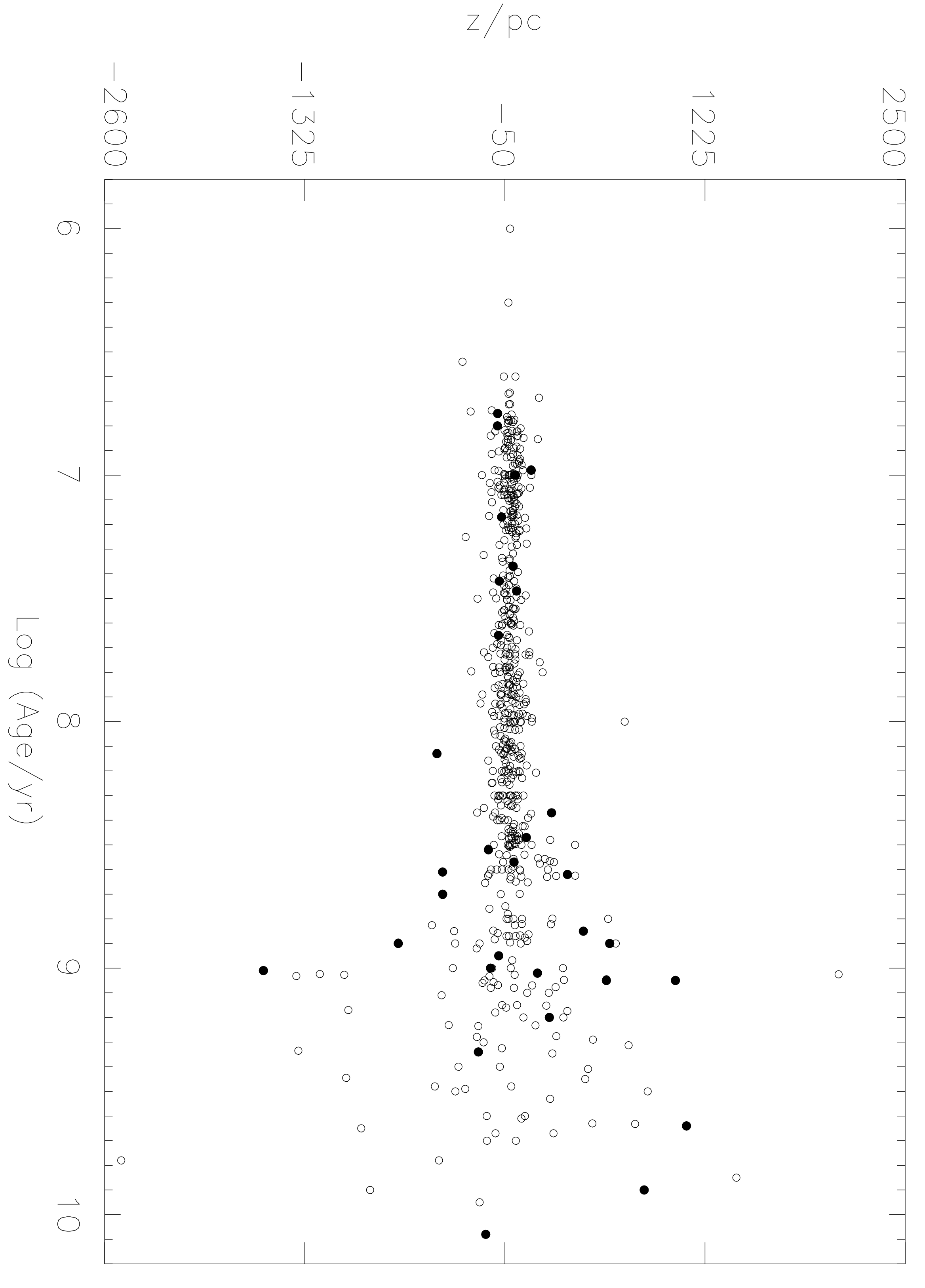

Fig. 5.— The age versus height from Galactic disk for open clusters in the Dias et al. (2002) catalog. Solid circles are the 31 open clusters studied in this paper.

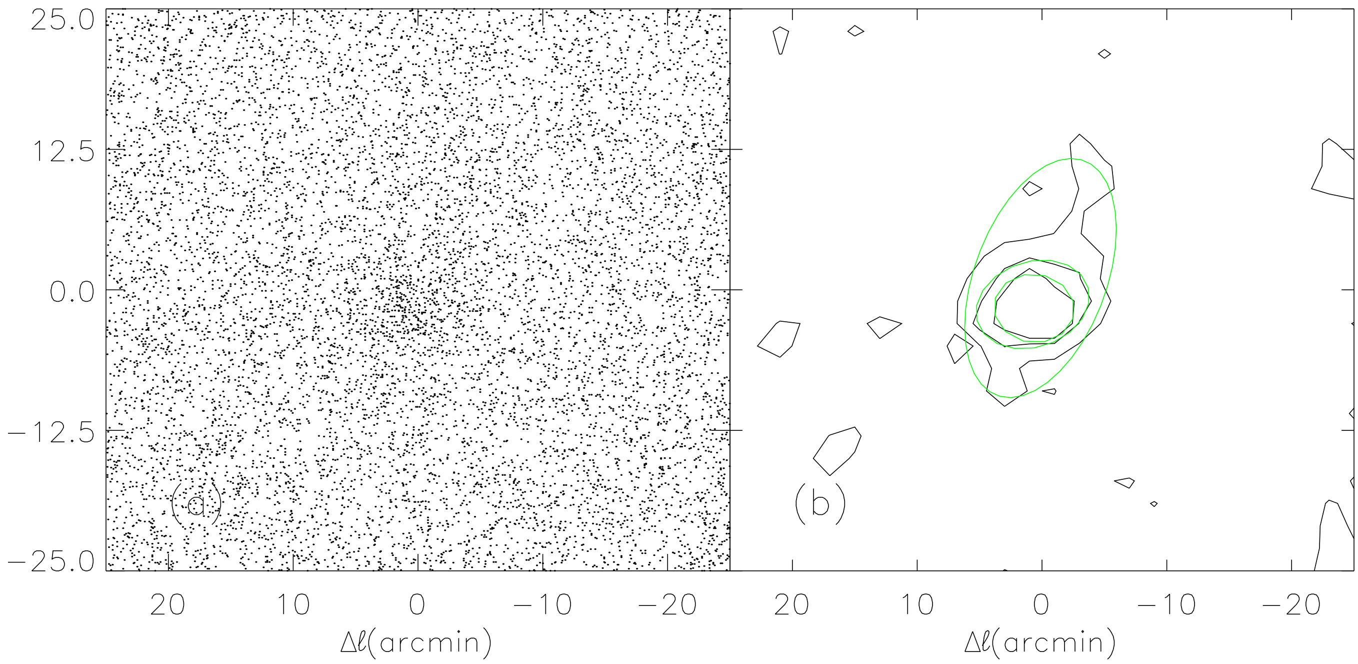

Fig. 6.— Morphology of the old open cluster Berkeley 17 ($\ell \sim 176\,\mathrm{deg}, b \sim -4\,\mathrm{deg}$) shows an upward tail toward Galactic disk. The outer boundary is duly fitted with an ellipse, obviously not appropriate here.

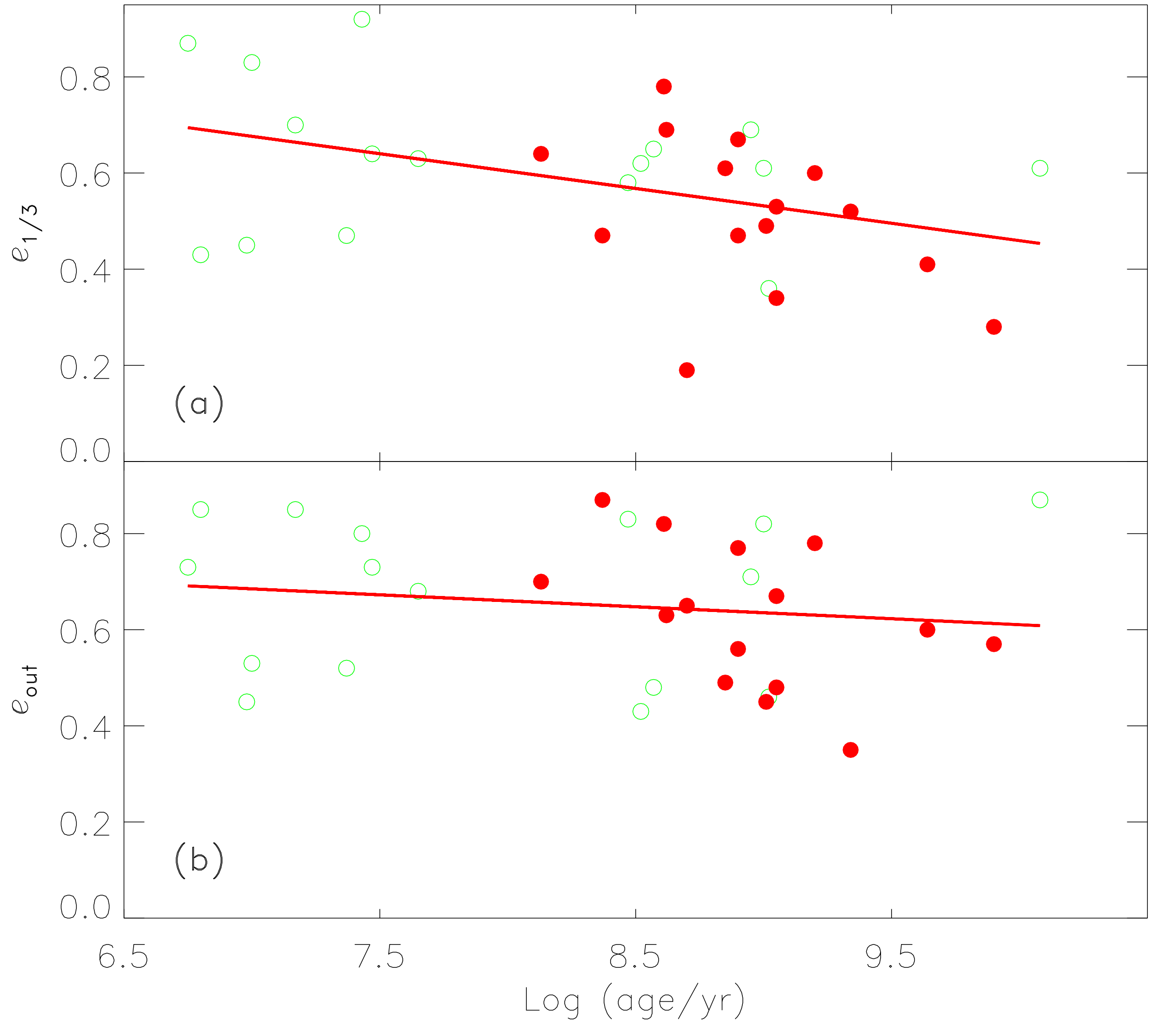

Fig. 7.— The ellipticity versus age of open clusters. Solid circles are for those which are relatively far from the Galactic plane than those, denoted by open circles, closer to the plane. Each solid line stands for a linear fit to the sample.

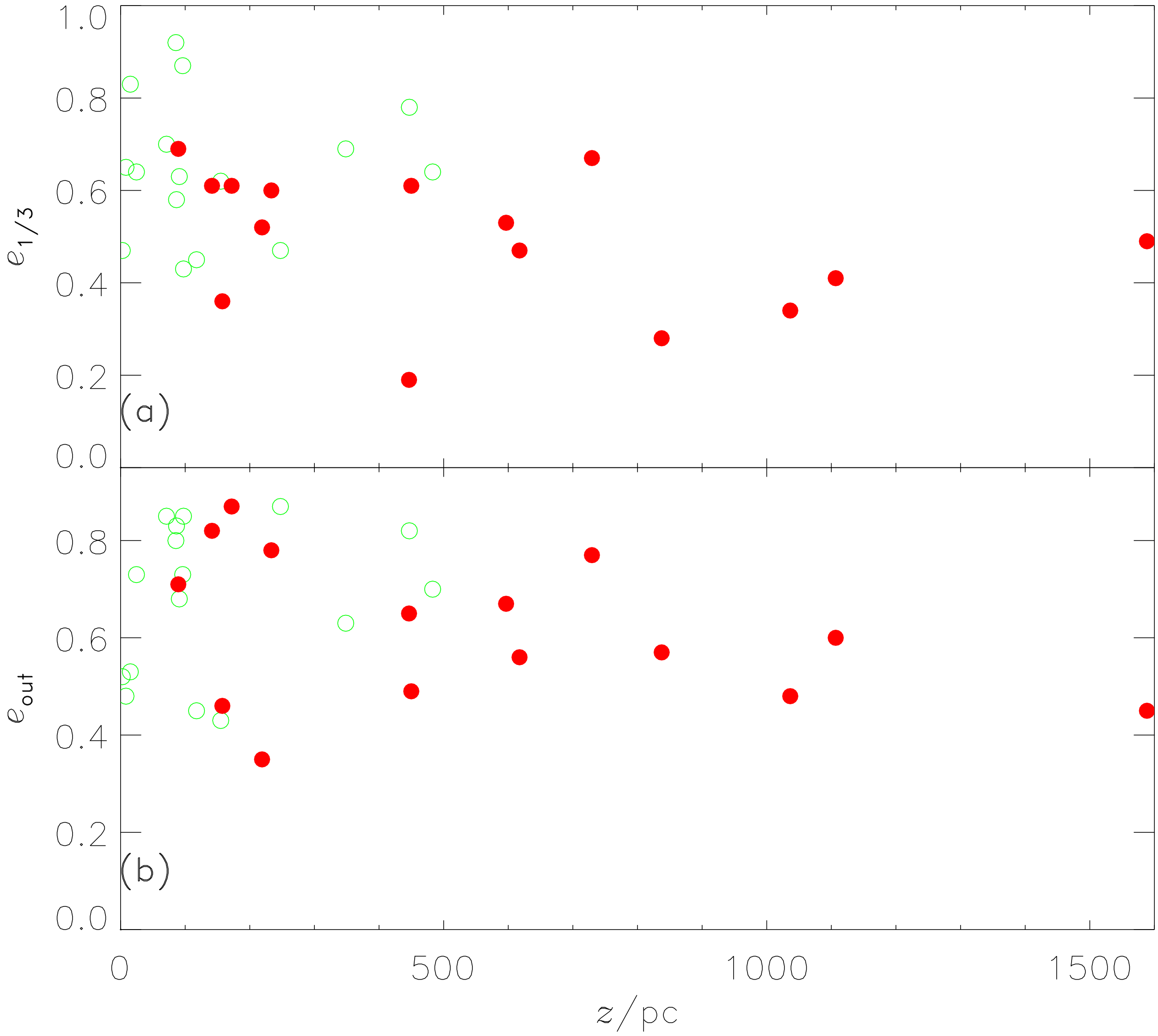

Fig. 8.— The ellipticity versus height of open clusters. Solid squares are for older star clusters and open squares are for young clusters.