ON THE GALACTIC DISK METALLICITY DISTRIBUTION FROM OPEN CLUSTERS. I.
NEW CATALOGS AND ABUNDANCE GRADIENT

L. CHEN, J. L. HOU, AND J. W. WANG
Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China;
chenli@center.shao.ac.cn, hjlyx@center.shao.ac.cn
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ABSTRACT

We have compiled two new open cluster catalogs. In the first one, there are 119 objects with ages, distances, and metallicities available, while in the second one, 144 objects have both absolute proper motion and radial velocity data, of which 45 clusters also have metallicity data available. Taking advantage of the large number of objects included in our sample, we present an iron radial gradient of about $-0.063 \pm 0.008$ dex kpc$^{-1}$ from the first sample, which is quite consistent with the most recent determination of the oxygen gradient from nebulae and young stars, about $-0.07$ dex kpc$^{-1}$. By dividing clusters into age groups, we show that the iron gradient was steeper in the past, which is consistent with the recent result from Galactic planetary nebulae data, and also consistent with inside-out galactic disk formation scenarios. Based on the cluster sample, we also discuss the metallicity distribution, cluster kinematics, and space distribution. A disk age-metallicity relation could be implied by those properties, although we cannot give conclusive result from the age-metallicity diagram based on the current sample. More observations are needed for metal-poor clusters. From the second catalog, we have calculated the velocity components in cylindrical coordinates with respect to the Galactic standard of rest for 144 open clusters. The velocity dispersions of the older clusters are larger than those of young clusters, but they are all much smaller than that of the Galactic thick disk stars.

Key words: Galaxy: evolution — Galaxy: formation — open clusters and associations: general

On-line material: machine-readable tables

1. INTRODUCTION

Since the seminal work of Eggen, Lynden-Bell, & Sandage (1962), great progress has been made in understanding the formation and evolution of the Milky Way galaxy. The progress comes on the one hand from observations concerning chemical abundances in stars (and clusters) and of gas clouds and, on the other hand, from improved knowledge regarding galaxy formation and evolution.

However, some important quantities related to the chemical evolution of our Galaxy, such as star formation history, initial mass function, gas flow, etc., are not yet well understood. Observational data from the Milky Way disk and halo have put strong constraints on our understanding of those quantities. Among a variety of observables, radial abundance gradients along the Galactic disk are one of the most important constraints on the Galactic chemical evolution model. The existence of such gradients is now well established, through radio and optical observations of H II regions, disk stars, planetary nebulae (Henry & Worthey 1999; Hou, Prantzos, & Boissier 2000; Chiappini et al. 2001; Maciel, Costa, & Uchida 2003), and open clusters (Friel 1995, 1999). An average gradient of about $-0.06$ dex kpc$^{-1}$ is observed in the Milky Way disk for most of the elements, e.g., O, S, Ne, Ar, and Fe. This magnitude of the observed gradients constrains the various parameters in the chemical evolution model, such as the timescales of star formation and infall (Prantzos & Aubert 1995) or any variations of the stellar initial mass function properties with metallicities (Chiappini et al. 2001).

In the last decade, a number of successful models have been developed relating to the chemical evolution of the Milky Way galaxy, but some important differences exist. One of them concerns the history of the abundance gradients along the Galactic disk: were they steeper or flatter in the past? Different predictions have been made by various models, although most of them claim that they could reproduce the majority of the observational properties both in the solar neighborhood and on the whole disk. Time-flattening evolution is suggested by the models of Prantzos & Aubert (1995), Molla, Ferrini, & Diaz (1997), Allen, Carigi, & Peimbert (1998), Boissier & Prantzos (1999), Tang et al. (1999, 2002), and Hou et al. (2000), while the opposite is supported by models of Tosi (1988), Samland, Hensler, & Theis (1997), and Chiappini et al. (1997, 2001).

The situation is also not settled observationally. Estimated ages of various types (PN I, PN II, PN III) of planetary nebulae (PNe) span a large fraction of the age of the Galaxy. Observations of the abundances of those objects across the Milky Way disk could, in principle, provide some information on the time evolution of the abundance gradient (Maciel & Köppe 1994; Maciel & Quiroga 1999; Maciel & Costa 2002; Maciel et al. 2003). In a recent work, Hou et al. (2000) have made a detailed analysis of the O, Ne, S, and Ar gradients based on the PN data of Maciel & Quiroga (1999). It was shown that there is fairly good agreement between model predictions and observations concerning all the properties of the observed abundance profiles (absolute values, gradient, scatter) for O, S, Ne, and Ar. The model suggests that abundance gradients are steeper in the earlier epoch. However, the large scatter in the adopted data does not allow one to make conclusions about the temporal variation of the gradients. Nevertheless, PNe suffer from large uncertainties concerning their progenitor’s masses and lifetimes as well as their distances from Galactic center.
On the other hand, open clusters (OCs) have long been used to trace the structure and evolution of the Galactic disk (Friel 1995). Since open clusters can be relatively accurately dated and we can see them to a large distance, their [Fe/H] values serve as an excellent tracer of the abundance gradient along the Galactic disk as well as many other important disk properties, such as the age-metallicity relation (AMR), abundance gradient evolution, disk age, and so on (Carraro, Ng, & Portinari 1998).

At this point, one might ask whether the field disk populations are also able to trace the disk evolution. Indeed, the extensive studies by Edvardsson et al. (1993), and recently by Chen, Nissen, & Zhao (2000), who concentrate on disk F and G stars, show an overall radial gradient that is nearly independent of age. Those results are based on stars mainly restricted to the solar neighborhood. A more detailed analysis of the disk iron gradient was given by Cui et al. (2000) on the basis of 1302 field stars with high-resolution proper motion and parallax data from the Hipparcos satellite. They have derived a radial iron gradient of $-0.057$ dex kpc$^{-1}$ within a Galactocentric distance of $8.5$–$17$ kpc. However, it is still difficult to deduce any pronounced gradient evolution from those results. Moreover, results from these studies are strongly affected by selection effects and rely on the techniques for determining individual stellar distances (which are heavily dependent on the adopted Galaxy potential model), which are much less reliable than those used to obtain cluster distances. In a recent work, Corder & Twarog (2001) have modeled the effects of the orbital diffusion of stars and clusters on the Galactic abundance gradient. The general conclusion is that the effect of diffusion makes a gradient shallower over time, and the cluster population offers a more viable means for finding detailed structure within the recent Galactic abundance gradient.

Here we also point out that our recent treatment of deriving the abundance gradient from open clusters in Hou, Chang, & Chen (2002) is in fact not proper. In that paper, we simply took four catalogs from the literature (Carraro et al. 1998; Twarog, Ashman, & Anthony-Twarog 1997, hereafter TAA97; Piatti, Claria, & Abadi 1995; Friel 1995), and merged them just by cross-checking for common clusters, without examining them individually to see whether there were important differences among the clusters in the different catalogs (B. A. Twarog 2002, private communication). Thus, the present paper should supersede the previous one.

In this paper, we compile a set of new open cluster catalogs. The catalog is divided into two parts: CAT 1 and CAT 2. In CAT 1, we list 119 clusters with iron abundance, age, distance, and reddening data available. This can provide statistically more significant information on Galactic disk formation and evolution, such as the age-metallicity relation, the abundance gradient and its time and/or spatial evolution, and so on. The second sample consists of 144 clusters with three-dimensional kinematic information available. From this sample, we are able to explore some statistical relations among kinematics and other observables.

The paper is organized as follows. First, in § 2, we describe the main characteristic of the two samples. Then, in § 3, we give some statistical analysis of the sample, mainly some metallicity and kinematic distributions. The abundance gradient is given in § 4. We show that, based on our open cluster data, the abundance gradient of the Galactic disk was steeper in the past. In § 5, we offer some detailed discussions of the AMR of the disk. Finally, a brief summary is given in § 6.

2. THE CATALOG

During the past decades, a number of authors have presented statistical studies of the Galactic disk based on their own open cluster catalogs. However, most of the catalogs suffer from either a lack of homogeneity in the cluster age and metallicity or insufficient three-dimensional kinematic data.

With the full release of Hipparcos Catalogue (ESA 1997) and the latest Tycho 2 catalog (Hog et al. 2000), we have seen a large growth of proper-motion data for open clusters (e.g., Baumgardt, Dettbarn, & Wielen 2000; Dias, Lépine, & Alessi 2001). A most recent compilation was given by Dias et al. (2002). Their catalog contained information on 1537 open clusters, of which 9% have both mean proper motion and radial velocity data simultaneously, and 37% have distance, $E(B-V)$, and age determinations, including 96 clusters that also have iron abundance data available.

We have compiled two new catalogs of the Galactic open clusters. The first one (CAT 1) lists 119 (including Berkeley 29) cluster parameters for distance, age, and metallicity. The age, distance, and reddening information are all (except for NGC 1348, NGC 2158, and Tombaugh 2) from Dias et al. (2002), and most iron abundance data (96 clusters) were also taken from Dias et al. (2002). The metallicities of another 23 clusters are from 10 other sources in the literature (Cameron 1985; Kubiak et al. 1992; Friel & Janes 1993; Friel 1995; Edvardsson et al. 1995; Piatti et al. 1995; Brown et al. 1996; Gratton 2000; Ann et al. 2002; Carraro, Girardi, & Marigo 2002).

Thus far, CAT 1 provides a most complete open cluster sample, having iron abundance, distance, and age parameters together. This sample could provide statistically more significant information concerning the Galactic AMR and radial iron gradient, as well as its evolution, etc.

In the second catalog (CAT 2), we have listed observed kinematical data from the literature for 144 clusters, with both radial velocity and mean proper motion available. The mean radial velocity data are mostly (122 of 144 objects) from a compilation in the WEBDA database, primarily based on the work of Rastorguev et al. (1999). The absolute proper motion of 125 clusters, based on the Hipparcos system, are from Baumgardt et al. (2000). Mean proper motions of an additional 16 clusters were added from the compilation of Dias et al. (2001), with cluster membership probability derived by Tycho 2 proper motions. Data on NGC 2355 come from Soubiran, Odenkirchen, & Le Campion (2000), and data on the Coma and Pleiades clusters are from Robichon et al. (1999). In fact, the above observed kinematic information constitutes a subcatalog of that of Dias et al. (2002). However, here in CAT 2 we have further calculated the three-dimensional velocity of open clusters by combing the radial velocity and mean absolute proper motion data and give, for each cluster, the velocity components $(\Pi, \Theta, W)$ in cylindrical coordinates with respect to the Galactic standard of rest (GSR). In addition, for each cluster, age and iron abundance data are also listed whenever available. (Note that in the spatial velocity

1 See http://obswww.unige.ch/webda/meanvr.html.
The following parameters are adopted for the Sun: Galactocentric distance 8.5 kpc, velocity components, and rotation velocity 225.0 km s$^{-1}$. The calculation, the following parameters are adopted for the Sun: Galactocentric distance 8.5 kpc, velocity components, and rotation velocity 225.0 km s$^{-1}$.

In order to check whether the data in our CAT 1 has any significant systematic difference with other published catalogs, we have made a comparison with Friel’s catalog (Friel 1995), with 41 clusters in common. We found that the average difference in metallicity is less than 0.10 dex, well within the typical observational uncertainty. The average difference for $R_{GC}$ is about 0.5 kpc. Note that the age indicator in Friel’s work is based on the morphological age index (MAI), which was only intended to provide a relative age ranking of clusters; therefore, it is not fully comparable. But there is still a good overall correlation between Friel’s catalog and ours.

Our analysis is mainly based on those two catalogs, but excluding cluster Berkeley 29. In CAT 1, Berkeley 29 has a Galactocentric radius of 23 kpc, $E(B-V)$ of 0.15, and a metallicity of −0.18 dex, from the compilation of Dias et al. (2002). However, different values for these parameters of Berkeley 29 have been published in the literature. Kaluzny (1994) gave a much smaller Galactocentric distance of about 19 kpc, reddening $E(B-V)$ larger than 0.21, and our analysis is mainly based on those two catalogs, but excluding cluster Berkeley 29.

### Table 1

| No. | Name       | $l$  | $b$   | $R_{GC}$ | $R_{v}$ | $E(B-V)$ | Age  | [Fe/H] | References |
|-----|------------|------|-------|----------|---------|----------|------|--------|------------|
| 1   | Berkeley 12 | 161.66 | -1.99 | 11.5     | 3162    | 0.7      | 4    | 0.07   | 1, 1       |
| 2   | Berkeley 17 | 175.65 | -3.65 | 11.1     | 2700    | 0.7      | 12.00| -0.33  | 1, 1       |
| 3   | Berkeley 18 | 163.63 | 5.01  | 14.1     | 5800    | 0.46     | 4.26 | 0.02   | 1, 1       |
| 4   | Berkeley 19 | 176.9  | -3.59 | 13.3     | 4831    | 0.4      | 3.09 | -0.50  | 1, 2       |
| 5   | Berkeley 20 | 203.51 | -17.28| 16.3     | 8400    | 0.12     | 6.02 | -0.75  | 1, 3       |

**Note.**—We list 119 clusters; in the paper, Berkeley 29 was not included in our calculations. Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

**References.**—(1) Dias et al. 2002; (2) Friel & Janes 1993; (3) Friel 1995; (4) Edvardsson et al. 1995; (5) Gratton 2000; (6) Ann et al. 2002; (7) Carraro et al. 2002; (8) Piatti et al. 1995; (9) Cameron 1985; (10) Kubiak et al. 1992; (11) Brown et al. 1996.

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### Table 2

| No. | ID       | $l$  | $b$   | $V_r$  | Reference | $\mu_{\alpha,\cos}\beta$ | $\mu_{\beta}$ | $R_{GC}$ |
|-----|----------|------|-------|--------|-----------|--------------------------|---------------|----------|
| 1   | NGC 129  | 120.3 | -2.6  | -36.8  | 1         | -1.86                    | -1.70         | 2        |
| 2   | NGC 188  | 122.8 | 22.5  | -44    | 1         | -1.48                    | -0.56         | 2        |
| 3   | NGC 457  | 126.6 | -4.4  | -34    | 1         | -1.56                    | -2.09         | 2        |
| 4   | NGC 581  | 128.0 | -1.8  | -37    | 1         | -1.60                    | 0.66          | 2        |
| 5   | NGC 654  | 129.1 | -0.4  | -33.8  | 1         | -1.34                    | -0.72         | 2        |

**Note.**—Table 2 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

**References.**—(1) Rastorguev et al. 1999; (2) Baumgardt et al. 2000; (3) Dias et al. 2002; (4) Mermilliod et al. 1996; (5) Friel 1993; (6) Lynga 1987; (7) Soubiran et al. 2000; (8) Mermilliod & Mayor 1990; (9) Mermilliod & Mayor 1989; (10) Mermilliod et al. 1995; (11) Mermilliod, Mayor, & Burki 1987; (12) Claria & Mermilliod 1992; (13) Scott, Friel, & Janes 1995; (14) Raboud & Mermilliod 1998; (15) Robichon et al. 1999.
based on the color-magnitude diagram (CMD) morphology and comparison to other old clusters, he also deduced a [Fe/H] value of less than $-1$. In the work of Noriega-Mendoza & Ruelas-Mayorgo (1997), who applied a new technique for simultaneous determination of [Fe/H] and $E(B-V)$, a [Fe/H] = $-0.30$ and $E(B-V) = 0.01$ were given for Berkeley 29. As the properties of Berkeley 29 are quite uncertain, we do not include this object in the following calculations. In general, the uncertainty for the metallicity determinations in open clusters is about 0.1 dex.

3. STATISTICAL PROPERTIES

3.1. The Galactic Distribution of Open Clusters

Using data from Dias et al. (2002) for 571 open clusters with distance and age data, we plotted the cluster positions on an $(X, Y)$ coordinate system, with the zero point in $X$ at the Galactic center (the Sun is assumed to be at 8.5 kpc), as Figure 1 shows. Here the solid line arc represents the solar circle about the Galactic center. One can see from this figure that in the Galactic plane, young clusters (with ages younger than that of Hyades, 0.8 Gyr; see Phelps, Janes, & Montgomery 1994) are distributed quite uniformly around the Sun, while only roughly 20% of the old clusters are inside the solar circle; most of the old ones are located farther away from the Galactic center than the Sun. This result is quite consistent with the early comprehensive study of Phelps et al. (1994). The deficiency of older clusters in the inner part of the disk has been ascribed to the preferential destruction of these clusters when they encountered giant molecular clouds, primarily found in the inner Galaxy.

The distribution of either old or young clusters perpendicular to the Galactic plane can be fitted by a simple exponential law, as plotted in Figure 2. The younger clusters are distributed on the Galactic plane almost symmetrically about the Sun, with a perpendicular scale height of approximately 57 pc. In contrast, about 80% of old clusters are in the outer disk, outside $R_{GC} = 10$ kpc; this population has a scale height of about 354 pc. The derived scale heights are in excellent agreement with the early results of Janes, Tilley, & Lyngå (1988) and Janes & Phelps (1994). Janes & Phelps (1994) divided the open clusters into young and old components according to cluster’s MAI, and derived their scale heights as 55 and 375 pc, respectively. The remarkable agreement shows that the MAI could really be a good age indicator for open clusters.

The main advantage of our CAT 2 is that we have both radial velocity and mean proper motion data available for 144 clusters. This provides a chance to probe the velocity projection on the Galactic plane, as shown in Figure 3. As can be seen in the figure, most of the clusters are located in the solar neighborhood and have velocity vectors that pretty well follow the Galactic rotational pattern.
3.2. The Metallicity Distribution

The metallicity distribution of 118 open clusters is plotted in the top panel of Figure 4. Here the iron abundance of about 3/4 of the OC sample (with [Fe/H] > −0.2) has a roughly Gaussian distribution, which peaks at the solar value. Meanwhile, a metal-poor metallicity tail is also clearly seen. Here we divide our OC sample into two groups, that is, metal-poor (MP) component and metal-rich (MR) component, with the dividing line between them, somewhat arbitrarily, at [Fe/H] = −0.2. In the bottom panel of Figure 4, we show two histograms for the open clusters of the above two groups. By assuming an exponential law, we can derive their scale heights to be 535 and 106 pc for the MP and MR components, respectively. Taking the scale heights of the Galactic thick and thin disk as 760 and 260 pc, respectively (Ojha et al. 1996), we can see that spatially, the MP group might be either within the tail of the thick disk or in the outskirts of the thin disk, while the MR group is just a thin-disk component. However, our OC metallicity sample is surely not a complete one, and is subject to a variety of observation effects. For example, the outer disk clusters are subject to significant selection effects—they can be seen more readily if they are at larger distances from the plane, and they are likely to be older, since younger clusters, which live closer to the plane, will not be as visible, and will be more difficult to observe.

This can also be seen clearly in Figure 5, where we have plotted the dependence of cluster vertical height on the Galactocentric distance for the whole sample with distances data available (Fig. 5a) and for those that also have metallicity data (Fig. 5b). In Figure 5b, we see that most of the MP OCs are outer-disk objects (with a median $R_{GC} \sim 11.3$ kpc), and the majority (65%) are older than 0.8 Gyr (see also Figs. 8 and 9, below) and relatively far away from the Galactic plane, with a median distance of about 326 pc. Most MR clusters are in the inner disk ($R_{GC} \leq 10$ kpc), distributing in the immediate solar neighborhood (with a median $R_{GC} \sim 8.7$ kpc), and about 78% are young objects (with ages <0.8 Gyr; see also Figs. 8 and 9, below). This phenomenon is very likely to imply the possible existence of the age-metallicity relation in open clusters.

Meanwhile, when $R_{GC} < 10$ kpc, most OCs, whether MP or MR, are much closer to the Galactic plane, with a median height $Z \sim 84$ pc. In particular, there are few clusters observed in the region of $R_{GC} < 6$ kpc. This has been attributed to the destructive power of the large numbers of giant molecular clouds in the inner regions of the Galaxy (van der Bergh & McClure 1980). There is much evidence that leads us to believe that open clusters have been selectively destroyed near the plane of the disk and only those clusters whose orbits keep them away from the Galactic plane can survive long enough to appear as outer-disk, or metal-poor, clusters. In the meanwhile, this also implies that some of the outer clusters (they are metal poor and with high $Z$) might be formed as a result of disturbances to the Galactic disk, possibly caused by tidal interactions with other galaxies or infalling gas, as suggested by Janes & Phelps (1994). However, it is still difficult to understand why there are almost no high-$Z$ clusters in the region of $R_{GC} \sim 6.5–8$ kpc, compared with the outer-disk results.

As a comparison, both globular and open cluster metallicity distribution are plotted in Figure 6. We can see a clear overlap between metal-rich globular clusters and metal-poor open clusters around [Fe/H] ≈ −0.4 dex. If the age-metallicity relation does exist, then this could be more evidence to support the idea that a possible connection
between the halo and disk population exists, in both their chemical and dynamical history.

Based on a survey of proper motion stars, Carney, Latham, & Laird (1990) pointed out that the Galactic halo population has a chemical and dynamical history almost independent of the disk. However, from a study of the oldest open clusters, Phelps et al. (1994) found that the oldest open clusters (Berkeley 17, with an age of about 12.5 Gyr) have ages comparable to those of the youngest globular clusters, suggesting that there may have been little or no time delay between the formation of the halo and the onset of the development of the disk. Phelps’s argument rests largely on the age of Berkeley 17 clusters; however, recent works have given an age of about 9 Gyr to this cluster (Carraro et al. 1999), and so there does still appear to be a gap between the formation of the halo and the thick disk. On the other hand, if cluster metallicity is related to age, the metallicity overlapping of the clusters, as we have presented, may be another indication of the connection proposed by Phelps et al. (1994). In fact, the distinction between “open” and “globular” (so-called “super”) clusters may turn out to be largely an artificial one (Larsen 2002). They could both originate from the super star clusters (SSCs), which are observed in large numbers in interacting galaxies and merger remnants. Our Milky Way disk has very likely undergone a process of minor mergers in the early epoch. The thick disk is plausibly the result of heating of the thin disk through such events (Wyse 2001).

3.3. Kinematics

In Figure 7, we plot the relation between cluster rotational velocities around the Galactic center, \( \Theta \), and the Galactocentric distance. There appears to be, from least-square fitting, an insignificant slope of about \(-2.5 \ \text{km s}^{-1} \ \text{kpc}^{-1} \), with quite large scatter. In the right panel, we present the dependence of velocity dispersion on the cluster age. The young clusters have a smaller velocity dispersion, which is expected from their small \( Z \) scale height. Although the velocity dispersion for the older clusters is about \( 20 \ \text{km s}^{-1} \), it is still much smaller than that of the Galactic thick-disk stars, which is about \( 50 \ \text{km s}^{-1} \). In any case, most of the CAT 2 clusters (90%) have heights from the Galactic plane well within 200 pc, and are just thin-disk objects.

In our kinematic sample, there are only two objects in the outer disk (Berkeley 31 and Dolidze 25, both with \( R_{GC} > 14 \ \text{kpc} \)). They have unreliable proper-motion and radial velocity results (with relative errors up to about 50%) and thus were not included in the above radial gradient fitting.

4. DISK METALLICITY GRADIENT FROM OPEN CLUSTERS

4.1. The Abundance Gradients

The first radial metallicity gradient using open clusters was given by Janes (1979), based on DDO and \( UBV \) photometric data of 41 disk objects (some of them are field stars). The derived gradient is \(-0.05 \ \text{dex kpc}^{-1} \). Panagia & Tosi (1981), by matching theoretical isochrones to H-R diagrams of 20 clusters with ages less than 1 Gyr, derived an iron abundance gradient of \(-0.095 \ \text{dex kpc}^{-1} \). A similar result was also obtained by Cameron (1985) based on 37 clusters with mixed ages. By introducing a weighting system in order to evaluate and compare the published parameters in the Lyngå (1987) Catalog of Open Clusters data, Janes et al. (1988) determined some basic parameters of 413 open clusters...
clusters, such as ages, distances, linear diameters, and so on. Among these, 87 open clusters have metallicity data. They have derived a gradient about $-0.133$ dex kpc$^{-1}$. By separating the clusters into age groups, they found that young clusters have much smaller gradient than that of older clusters. In addition, all these authors found some indications that the gradient became shallower in the direction of the Galactic center and steepened in the outer parts of the Galaxy.

Friel & Janes (1993, hereafter FJ93) presented their results from a spectroscopic study of a sample of giant stars in 24 open clusters. They derived a Galactocentric radial abundance gradient of $[\text{Fe/H}]$ of about $-0.088$ dex kpc$^{-1}$. A subsequent revision of the FJ93 result was presented by Friel (1995), using additional spectroscopic results and a more uniform set of cluster properties. From a sample of 44 clusters, Friel (1995) derived an iron gradient of $-0.091$ dex kpc$^{-1}$. At the same time, Piatti et al. (1995) derived a much smaller gradients, $-0.07$ dex kpc$^{-1}$, from a sample of 63 open clusters with a wide range of ages. These results are quite consistent with the recent result of Friel (1999), who obtained a gradient of about $-0.06$ dex kpc$^{-1}$. Another gradient result was recently presented by Carraro et al. (1998). The metallicities of all selected 37 clusters were obtained spectrophotically. The final gradient was about $-0.085$ dex kpc$^{-1}$, agreeing with earlier result of FJ93. By dividing the sample into age bins, it was found that the present-day gradient is a little shallower than the past one, while the middle epoch seems to display a steepening of the gradient.

The presence of a linear gradient for open clusters has been questioned by TAA97. TAA97 put forth an alternative description, namely, step function, for the radial abundances distribution of the open clusters. Within their work, a set of 76 clusters with abundances based on DDO and/or moderate dispersion spectroscopy has been transformed to a common metallicity scale and used to study the local structure and evolution of the Galactic disk. They found that the metallicity distribution of clusters with Galactocentric distance is best described by two distinct zones, with a sharp discontinuity at $R_{GC} = 10$ kpc. Between $R_{GC} = 6.5$ and 10 kpc, the clusters have a mean metallicity of 0.0 dex with, at best, weak evidence for a shallow gradient over this range, while those beyond 10 kpc have a mean value of about $-0.30$ dex. This two-step distribution seems quite similar to the nebula results of Simpson et al. (1995). Neglecting this two-step phenomena, a least-square fitting results in a gradient of about $-0.067$ dex kpc$^{-1}$ between 6 and 15 kpc if cluster Berkeley 21 is excluded (because both the metallicity and distance of this object are quite uncertain).

The existence of radial iron abundance gradients is also confirmed by our new up-to-date sample. The result is shown in the Figure 8a. By equal-weighted least-square fitting, we derived a radial abundance gradient of $-0.063 \pm 0.008$ dex kpc$^{-1}$, which agrees well with most of the previous open cluster results. It is also similar to the gradients obtained from other tracers, such as disk H II regions and planetary nebulae (see a summary in Hou et al. 2000 ). The existence of a gradient along the Galactic disk provides a good opportunity to test theories of disk evolution and stellar nucleosynthesis. It suggests that the role of the Galactic bar in inducing large-scale radial mixing and therefore flattening the gradient has been rather limited; alternatively, the bar could be too young (<1 Gyr) to have brought any important modifications to the gaseous and abundance pro-

file. However, we must note that our current knowledge of the iron gradient as derived from open clusters is far from being clear. Open clusters span a wide range of ages, from several millions of years to several Gyr; therefore, they do not trace the young component of the Galactic disk. The result we obtained is somewhat an averaged one (over age). The obtained similarity of gradients between iron and other elements, such as oxygen, is quite surprising, since the sites of nucleosynthesis for iron and oxygen are quite different. It is well know that iron is mainly produced in Type Ia supernovae (SNe Ia), while oxygen is largely a product of SNe II, that is, from massive stars. So the abundance history is very different for those two types of elements. The gradient similarity might be simply coincidental, but further investigation should be made into the nature of the production of those elements.

We also derived a vertical abundance gradient of $-0.295 \pm 0.050$ dex kpc$^{-1}$ (Fig. 8b). This is consistent with the result of Carraro et al. (1998).

4.2. Gradient Evolution in the Galactic Disk

As we have pointed out in §1, the behavior of gradient evolution along the Galactic disk is a major problem for different chemical evolution models. Open cluster systems are an ideal template for this analysis because OCs have relatively well determined ages, distances, and metallicities.

In Figure 9a, we show gradients for two subsamples with cluster ages <0.8 Gyr (80 clusters) and >0.8 Gyr (38 clusters), respectively. The fitting results are $-0.024 \pm 0.012$ dex kpc$^{-1}$ for younger clusters, and $-0.075 \pm 0.013$ dex kpc$^{-1}$ for older ones. If we take the mean age for the youngest and oldest clusters as 0.00 and 6.00 Gyr, respectively (this is somewhat arbitrary, just for illustration purpose) in our sample, we can estimate an average flattening rate of 0.008 dex kpc$^{-1}$ Gyr$^{-1}$ during the past 6 Gyr. A similar value is obtained by Maciel et al. (2003) from PN data for [O/H].

As we have indicated in §1, the time evolution of the abundance gradient along the Galactic disk is crucial in

![Fig. 8.—(a) Radial and (b) vertical abundance gradient for 118 open clusters. The least-square fitting results in a gradient of $-0.063 \pm 0.008$ and $-0.295 \pm 0.050$ dex kpc$^{-1}$, respectively.](image-url)
discriminating different theoretical models that adopt various prescriptions for the time dependence of the star formation rate and the infall. Our current open cluster sample could surely provide some insights on this subject. The time-flattening tendency we obtained supports the “inside-out” disk formation scenarios, with infall timescale dependent on radius from the disk center (Boissier & Prantzos 1999; Hou et al. 2000; Chang et al. 2002).

In Figure 9b, we divide clusters into inner (<10 kpc) and outer groups. The corresponding gradients are $-0.040 \pm 0.022$ and $-0.047 \pm 0.023$ dex kpc$^{-1}$, respectively. We can see that the inner disk exhibits roughly the same (or a bit smaller) gradient as the outer part. This result is also consistent with the abundance gradient determined by using Cepheids in the solar neighborhood (Andrievsky et al. 2002). However, in our CAT 1, the innermost cluster is located at a Galactocentric distance of about 6.8 kpc, so it is necessary to have more inner cluster data (between 3 and 7 kpc) in order to further check the gradient behavior for the inner disk. If the Galactic bar does play the role, then the inner gradient could be flatter than the outer part.

Our cluster sample is nearly 50% larger than that of TAA97, and we did not find evidence of any abrupt discontinuity. A similar conclusion was reached by Friel (1999), using high-resolution abundance determinations for metallicity calibration.

5. DISK AGE–METALLICITY RELATION

The AMR for the Galactic disk provides useful clues about the chemical evolution history of the Milky Way, and also puts an important constraint on the theoretical models of the disk. The observed abundance data generally show a decrease of the stellar metallicity with increasing stellar age, indicating a continuous growth of the metals in the ISM during the life of the Galaxy. The early study on AMR for nearby stars by Twarog (1980) found that the mean metallicity of the disk increased by a factor of 5 between 12 and 5 billion year ago and has increased only slightly since then. This was also confirmed by latter photometric survey of Meusinger, Stecklum, & Reimann (1991). With the high-resolution spectroscopic data, Edvardsson et al. (1993) showed a plot of iron abundance versus relative ages for the 189 stars in the solar neighborhood. The overall trend of a slowly increasing abundance with decreasing age was consistent with the previous photometric results. However, the most striking feature of their result is the large scatter around the average trend, which marks a weak correlation between age and metallicity. This spread was, as they pointed out, in part due to selection bias for the programme stars, and at least partly intrinsic, since the mean errors in [Fe/H] measurement and logarithmic age derivation are much less than the scatter.

In a recent paper, Feltzing, Holmberg, & Hurley (2001) have reexamined the Galactic AMR in the solar neighborhood based on a sample of 5828 dwarfs and subdwarfs from the Hipparcos Catalogue. They found that the solar neighborhood age-metallicity diagram is well populated at all ages and especially that old, metal-rich stars do exist that have been omitted in previous samples. This indicates a complete lack of enrichment over the age of the Galactic disk among the fields stars in the solar neighborhood.

Using open clusters to explore the AMR has a main advantage in both abundance and age determinations, since one is dealing with a group of stars and the result is less susceptible to individual errors (Carraro et al. 1998). Cameron (1985) was the first to probe the AMR from open cluster data, and found no age-metallicity relation based on his cluster sample. This is not surprising, since the metallicity of the Galactic disk increased only slightly during the past 5 Gyr, while his sample of 38 clusters contained no objects older than 5.1 Gyr. More recently, Carraro et al. (1998) compiled a relatively homogenous sample of 37 open clusters. The data have more expanded cluster ages up to 9 Gyr. After correcting for the radial abundance gradient, the derived AMR showed a trend similar to that of nearby stars.

In this paper, we present a new open cluster catalog with many more objects. The results, based on this larger sample, should be statistically more reliable. As we have shown in the § 3.2, statistically, the space distributions (scale heights for metal-poor and metal-rich groups, for young and old clusters) of open clusters very likely imply the existence of an age-metallicity relation in the Galactic disk. In Figure 10, we plot the dependence of metallicity on the cluster age, after correcting the radial metallicity gradient. Unfortunately, it is difficult to draw any conclusive indication for AMR based on this plot because of the deficiency of very old clusters. More observational efforts should be made to find more older clusters.

The significant spread of the AMR seems real, but its origin is not yet clear. For the scatter in the AMR of nearby stars, many possible causes have been suggested, such as orbital diffusion of stars, inhomogeneous chemical enrichment in the Galaxy evolution, overlapping of different Galactic substructures, and so on. All of the above-mentioned effects may contribute to the observed scatter, while for open clusters, the result should not be very sensitive to orbital diffusion effects (Corder & Twarog 2001). Therefore, the scatter of the AMR along the Galactic disk from both clusters and field disk stars is an essential feature in the formation and evolution of the Milky Way.
The main work of this paper has been to compile the most complete open cluster sample with metallicity, age, and distance data, as well as kinematic information, available. In addition, some statistical analysis on spatial and metallicity distributions have been made on this sample. We derived an iron radial gradient of about $-0.063 \pm 0.008$ dex kpc$^{-1}$ from CAT 1, which is quite consistent with the most recent determination of the oxygen gradient in nebulae and young stars. By dividing clusters into age groups, we show that the iron gradient was steeper in the past, which is consistent with the recent results from Galactic planetary nebulae data. Our result supports the inside-out Galactic disk formation mechanism, in which the invoked star formation rate and infall timescale vary with radius.

We also explore the spatial variation of gradient. When the clusters are divided into inner and outer groups, we find that the abundance gradient is a bit shallower inside 10 kpc. However, the innermost cluster in our sample is at $R_{GC} = 6.8$ kpc; we need more data on clusters in the inner region. This could be helpful in judging the radial flow effect on the current Galactic chemical evolution model.

From scale heights of metal-poor and metal-rich clusters, we note that the metallicity could be related to the age. However, directly plotting the dependence of cluster abundances on their ages, no striking slope in AMR is found, although the paucity of metallicity of very old open clusters makes it impossible to give a definite conclusion based on the current sample.

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