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Properties of Open Clusters Containing Blue Stragglers

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Abstract: The presence of blue stragglers pose challenges to standard stellar evolution theory, in the sense that explaining their presence demands a complex interplay between stellar evolution and cluster dynamics. In the meantime, mass transfer in binary systems and stellar collisions are widely studied as a blue straggler formation channel. We explore properties of the Galactic open clusters where blue stragglers are found, in attempting to estimate the relative importance of these two favored processes, by comparing them with those resulting from open clusters in which blue stragglers are absent as of now. Unlike previous studies which require a sophisticated process in understanding the implication of the results, this approach is straightforward and has resulted in a supplementary supporting evidence for the current view on the blue straggler formation mechanism. Our main findings are as follows: (1) Open clusters in which blue stragglers are present have a broader distribution with respect to the Z-axis pointing towards the North Galactic Pole than those in which blue stragglers are absent. The probability that two distributions with respect to the Z-axis are drawn from the same distribution is 0.2%. (2) Average values of $\log_{10}(t)$ of the clusters with blue stragglers and those without blue stragglers are 8.58 ± 0.232 and 7.52 ± 0.285, respectively. (3) The clusters with blue stragglers tend to be relatively redder than the others, and are distributed broader in colors. (4) The clusters with blue stragglers are likely brighter than those without blue stragglers. (5) Finally, blue stragglers seem to form in *condensed* clusters rather than simply *dense* clusters. Hence, we conclude that mass transfer in binaries seems to be a relatively important physical mechanism of the generation of blue stragglers in open clusters, provided they are sufficiently old.

Key words: stars: blue stragglers — open clusters and associations: general

1. Introduction

Blue stragglers are commonly defined as stars brighter and bluer (i.e., hotter) than the turnoff in the color-magnitude diagram (Shara et al. 1997; Gilliland et al. 1998; De Marco et al. 2004; Fiorentino et al. 2014). Since their first discovery in the globular cluster M3 by Sandage (1953), blue stragglers have been abundantly detected in open clusters (Ahumada & Lapasset 1995, 2007; de Marchi et al. 2006), in globular clusters (Fusi Pecci et al. 1992; Piotto et al. 2004), in OB associations (Schild 1985; Mathys 1987), and even in dwarf galaxies (Da Costa 1984; Carney & Seitzer 1986; Momany et al. 2007; Mapelli et al. 2009). The presence of blue stragglers has posed challenges to the standard stellar evolution theory, since stars with masses higher than the turnoff mass in the star cluster should long ago have evolved off the main sequence toward the red giant branch. In order to explain their existence along an extension of the main sequence the complex interplay between stellar evolution and cluster dynamics has to be taken into account.

Despite numerous efforts to explain their presence, no general mechanism resulting in straggling away from the regular evolutionary path has been proposed yet. In the meantime, favored formation channels involve either mass transfer in binary systems possibly up to complete coalescence of the two stars (McCrea 1964; Mateo et al. 1990; Preston & Sneden 2000; Carney et al. 2001; Ferraro et al. 2003; Davies et al. 2004; Mapelli et al. 2004; Ferraro et al. 2006; Lu et al. 2011; Sollima et al. 2008; Knigge et al. 2009; Mathieu et al. 2009; Geller & Mathieu 2011; Gosnell et al. 2014) or stellar collisions (Hills & Day 1976; Bailyn 1992, 1995; Leonard & Linnell 1992; Ferraro et al. 1993, 1997, 2003; Lombardi et al. 1996, 2002; Sills & Bailyn 1999; Glebbeek et al. 2008; Chatterjee et al. 2013), in both of which fresh hydrogen fuel is supposed to be brought into the energy generation core so that the star can be rejuvenated to its main sequence stage (Lombardi et al. 1995; Sills et al. 2001, 2002; Chen & Han 2009).

A result supporting mass transfer during the binary evolution as the dominant channel for blue straggler formation, Piotto et al. (2004) have shown that the relative number of blue stragglers found in the core of a globular cluster is strongly anticorrelated with the absolute luminosity (and hence mass) of the host cluster, but not with the central density, nor the collision rate in the core. A similar trend between the blue straggler frequency and the total luminosity has been also confirmed in Galactic open clusters (de Marchi et al.

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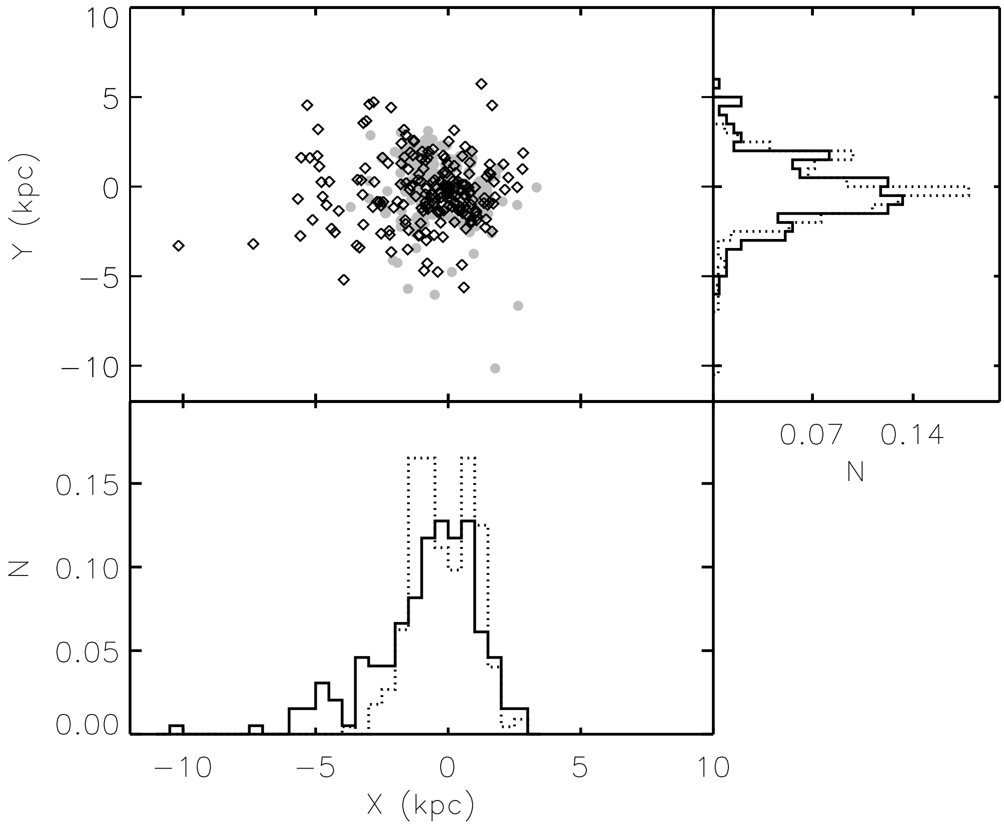

Figure 1. Positions of the open clusters we analyzed in this study in the rectangular Galactic coordinates X and Y axes, and the number distribution of clusters obtained by projecting to X and Y axes. Open diamonds and gray dots denote clusters in which blue stragglers are present and those in which blue stragglers are absent, respectively. The solid and dotted histograms result from the clusters hosting blue stragglers and those without blue stragglers, respectively. Note that all the histograms produced in this paper are normalized such that the total area is equal to unity.

2006). Leigh et al. (2007) using the Padova Galactic cluster database have further tried to correlate the blue straggler frequency with the other cluster parameters, and found the lack of any correlation of the collisional parameters with the blue straggler population. Consequently, they have claimed that blue stragglers should be mostly born in binary systems and not from direct star encounters.

On the other hand, wide-field studies show a clear bimodality in the radial distribution of blue stragglers in star clusters (Ferraro et al. 1993, 1997, 2001, 2009, 2012; Zaggia et al. 1997; Clark et al. 2004; Sabbi et al. 2004; Warren et al. 2006; Beccari et al. 2006), probably implying that different formation mechanisms play a prominent role in different environments. The detailed properties of the bimodal distribution indeed seem to correlate with the dynamical evolution of globular clusters. Based on the observational evidence, Mapelli et al. (2006) proposed a model in which mass transfer in binary systems and collisional blue straggler formation mechanisms are at work at the same time and have almost the same efficiency throughout the evolution of the cluster. In the proposed scenario, blue stragglers in the dense core have a collisional origin, whereas blue stragglers in the low-density cluster outskirts were formed by mass transfer in primordial binaries. Furthermore, the luminosity function of blue stragglers indicate that clusters with different luminosities host different populations of blue stragglers (Moretti et al. 2008). Hence it was suggested that less luminous clusters produce more blue stragglers via mass transfer, while in more luminous ones collisions should play a more important role (Hurley et al. 2001; Davies et al. 2004). In other words, observations probably seem to support the idea that neither model can adequately produce the entire blue straggler population so the most likely explanation is some combination of the two (Ferraro et al. 2009; Dalessandro et al. 2013).

In this paper, our attention is on open clusters in which blue stragglers are formed. We explore properties of the Galactic open clusters from which blue stragglers are extracted, in attempting to estimate the relative importance of these two favored processes. To this end, we divide the open clusters in the Galactic open cluster catalog (Ahumada & Lapasset 2007) into two subgroups based on whether or not blue stragglers are found in the clusters, and statistically compare environments and related parameters of the clusters hosting blue stragglers with those in which blue stragglers are not found. In an attempt to better understand the formation of blue

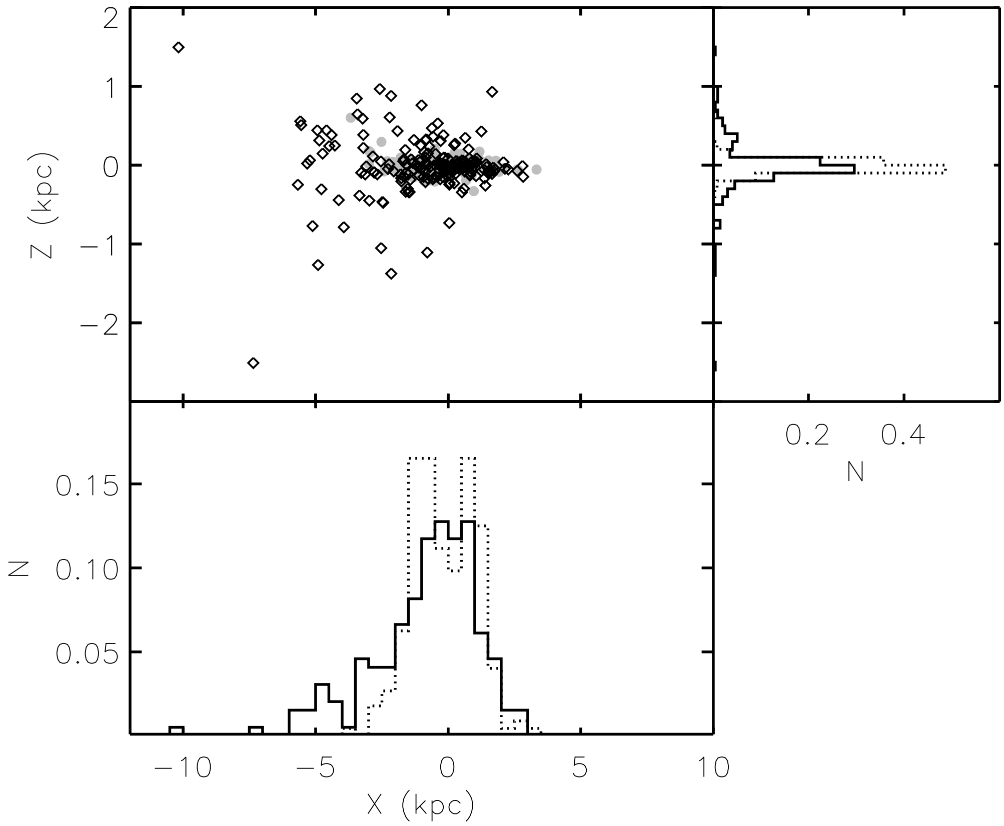

Figure 2. Same as Figure 1, except that data are for the rectangular Galactic coordinates X and Z.

stragglers, we use the simple presence of a blue straggler to flag clusters. The number of blue stragglers in a cluster is likely to be affected by many factors such as binarity, mass, local density, age of clusters etc. In this sense, a simple-minded comparison between clusters with blue stragglers and those without could give some insight into mechanisms driving the formation of these objects.

The main differences of the current analysis from most previous works are as follows: (1) the latter presented observational evidence verifying or disproving possible correlations between blue straggler properties and some dynamically important cluster property, such as, the collision rate estimate or the total cluster mass, of an *individual* cluster hosting blue stragglers, particularly of a globular cluster (e.g., Fusi Pecci et al. 1992; Piotto et al. 2002, 2004; Sollima et al. 2008; Ferraro et al. 2012; Li et al. 2013). The reason selecting an individual globular cluster for the study is partly because it is more difficult to study blue stragglers in open clusters than in globular clusters in a systematic manners, as the observed blue stragglers in younger clusters are generally limited by the small number of more massive stars than the turnoff. (2) they attempted to reveal possible dependencies of the number of blue stragglers in clusters as a function of distance from the core of the cluster (e.g., Ferraro et al. 1993, 2004; Zaggia et al. 1997; Sabbi et al. 2004; Warren et al. 2006; Dalessandro et al. 2008, 2009; Contreras Ramos et al. 2012; Beccari et al. 2011, 2013; Baldwin et al. 2016). Even though the relative importance of the efficiency of blue straggler production mechanisms vary with the characteristics of clusters, it is quite clear that the observed correlations can only give suppositional information about the role of the dynamics on stellar evolution. Direct understanding of these processes is impossible without due theoretical modeling, while these observed relations can tell us about formation channels of blue stragglers. In addition to this drawback it may be risky to use *observed* blue straggler populations as a basis for theoretical speculations particularly when an individual cluster is studied, since several clusters might have more blue stragglers in their very crowded central regions where individual stars are not resolved.

This paper is organized as follows. We begin with brief descriptions of the data sets of the open clusters analyzed in Section 2. We present results of analysis and discuss the implications of our findings in Section 3. Finally, we summarize and conclude in Section 4.

2. Data

The clusters used for the present study are basically adopted from the Galactic open cluster catalogue described by Ahumada & Lapasset (2007). It has updated and superseded the earlier version (Ahumada & Lapasset 1995), in which blue stragglers are selected by the inspection of color-magnitude diagrams of clusters. There, 1887 blue stragglers are identified in open clus-

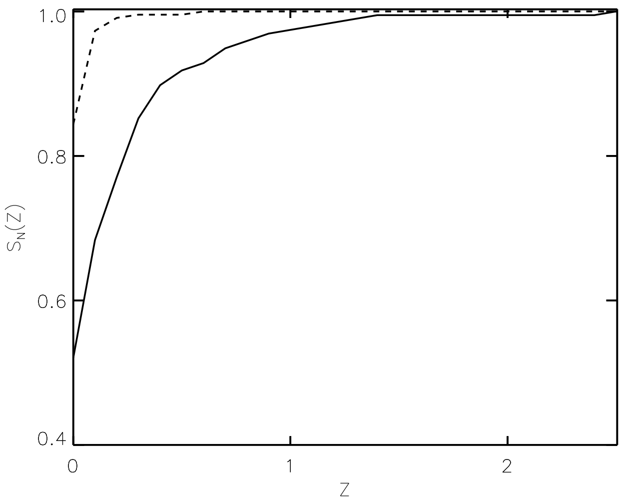

Figure 3. Cumulative distribution functions of the number distribution along the Z-axis of the open clusters. The solid and dotted histograms result from the clusters hosting blue stragglers and those without blue stragglers, respectively.

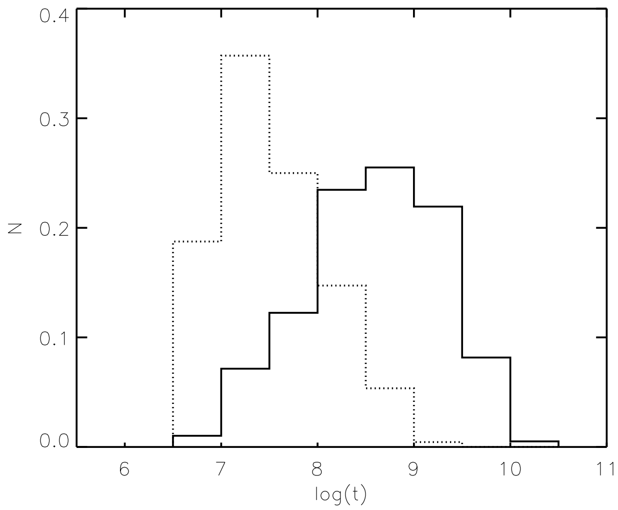

Figure 4. Distribution of logarithms of the age of the clusters. The solid and dotted histograms result from the clusters hosting blue stragglers and those without blue stragglers, respectively.

ters of all ages. The number of clusters with at least one blue straggler is 199 out 427 in total (i.e., 46.6% of the total). A cluster is counted as hosting blue stragglers even if there is only one straggler present in it. We refer readers to the original paper for a careful description of selection mechanism (Ahumada & Lapasset 2007 and references therein).

Additional parameters of the clusters we have analyzed here, such as, spatial, structural, and astrophysical parameters, which are not provided by Ahumada & Lapasset (2007), are adopted from the catalogue listed by the Milky Way Star Clusters (MWSC) project (Kharchenko et al. 2012, 2013, 2016, and references therein).

3. RESULTS AND DISCUSSION

In Figures 1 and 2, we show positions of the open clusters we analyzed in this study in the rectangular Galactic coordinate system, where X-axis points from the position of the Sun projected to the Galactic midplane to the Galactic center, the Y-axis points towards Galactic longitude $l = 90°$, and the Z-axis points towards the North Galactic Pole ($b = 90°$). By definition, thus, the position of the Sun marks at $(0, 0)$ in each Figure. Open diamonds and grey dots denote clusters in which blue stragglers are present and those in which blue stragglers are absent. It should be mentioned that all the plots only include 420 open clusters in our sample taken from Ahumada & Lapasset (2007), not all the clusters in the Milky Way. We include only 420 instead of 427, since observational data in Kharchenko et al. (2012, 2013, 2016) only cover the 420 open clusters. One may see, however, that the open clusters shown here cover a wide range of distances so that conclusions made in the current study could be considered as unbiased. The number distribution of clusters obtained by projecting to the specific axis is also shown along the corresponding axis in the right and bottom panels of Figures 1 and 2. Note that all the histograms produced in this paper are normalized such that the total area is equal to unity. The solid and dotted histograms result from the clusters hosting blue stragglers and those without blue stragglers, respectively.

It is interesting to note that clusters in which blue stragglers are present seem to have a broader distribution with respect to the Z-axis, unlike X-axis and Y-axis, than those in which blue stragglers are absent, even though their mean values are almost identical. For instance, the proportion of clusters with blue stragglers grows as one moves further out from the midplane of the Galaxy. All clusters at distances higher than ~ 0.5 kpc from the midplane contain at least one blue straggler. On the other hand, at distances lower than ~ 0.5 kpc, only about half of all the clusters host blue stragglers. Clusters in the midplane of the Galaxy are mostly without blue stragglers. To statistically check if the two distributions resulting from two open cluster subgroups are consistent each other we perform the Kolmogorov-Smirnov (K-S) test as shown in Figure 3. The probability that two distributions with respect to the Z-axis are drawn from the same distribution is 0.2% using the K-S statistic d. This is defined as the maximum value of the absolute difference between two cumulative distribution functions being 0.39. For comparison, we repeat the test on two distributions with and without blue stragglers with respect to the X-axis and Y-axis, and obtain the probabilities of $\sim 10\%$ and $\sim 16\%$, respectively. The distribution seemingly indicates that the age distribution of the clusters with blue stragglers are different from that without blue stragglers.

In Figure 4, the distribution of logarithms of the age of the clusters is also shown to make sure. Average values of $\log_{10}(t)$ of the clusters with blue stragglers and those without blue stragglers are 8.58 ± 0.232 and

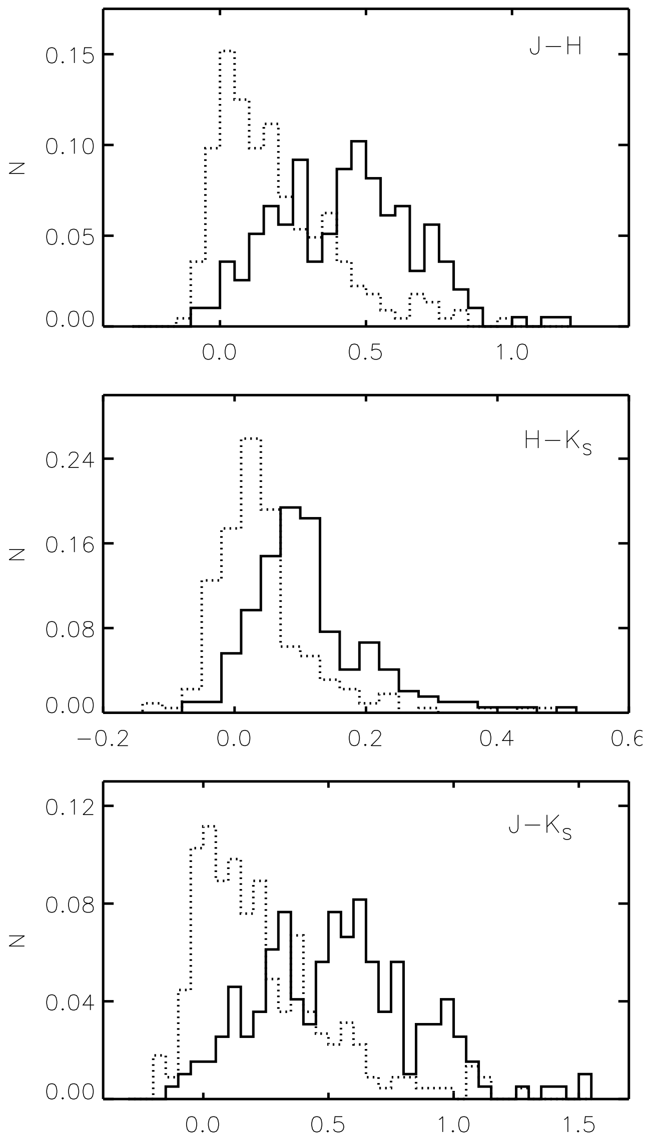

Figure 5. Distributions of integrated colors of the clusters. From top to bottom panels colors are defined as $J - H$, $H - K_S$, and $J - K_S$, respectively. The solid and dotted histograms result from the clusters hosting blue stragglers and those without blue stragglers, respectively.

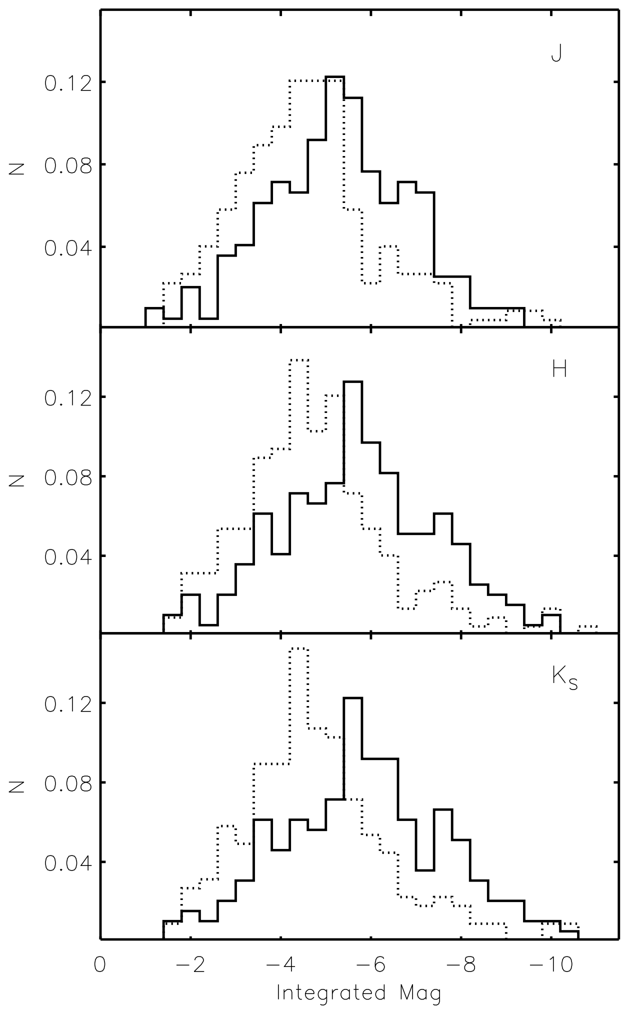

Figure 6. Distributions of the integrated absolute magnitudes of the clusters. From top to bottom panels the absolute magnitudes are J, H, K_S, respectively. The solid and dotted histograms result from the clusters hosting blue stragglers and those without blue stragglers, respectively.

7.52 ± 0.285, respectively. This result is in agreement with the previously known fact that both the absolute number and the normalized number of blue stragglers in the clusters in which blue stragglers are found increase with the age (i.e., de Marchi et al. 2006; Ahumada & Lapasset 2007). Hence, one reminds oneself that a physical mechanism of the generation of blue stragglers should have a productivity growing with time, such as, mass transfer in binary.

In Figure 5, we show distributions of integrated colors of the clusters. From top to bottom panels colors are defined as $J - H$, $H - K_S$, $J - K_S$, respectively. In a sense, what is seen here seems to reflect the distribution of logarithms of the age of the clusters. The clusters with blue stragglers tend to be relatively redder than the others, and are distributed broader in colors. Averaged values of the colors $J - H$, $H - K_S$, $J - K_S$ of the clusters hosting blue stragglers are $0.43 \pm 0.170, 0.11 \pm 0.074, 0.54 \pm 0.235$ whereas those of the clusters without blue stragglers are $0.19 \pm 0.185, 0.09 \pm 0.084, 0.23 \pm 0.270$, respectively. One more thing to note is that these distributions for clusters without blue stragglers can be fitted to the Poisson distribution with a sharp increase at the blue side, instead of a Gaussian-like symmetrical distribution that can be fitted to the distribution of the clusters hosting blue stragglers.

In Figure 6, we show the distributions of the integrated absolute magnitudes of the clusters. From top to bottom panels the absolute magnitudes are J, H, K_S, respectively. As expected from the observations showing that the number of blue stragglers increases with the brightness of the cluster (e.g., de Marchi et al. 2006; Moretti et al. 2008), the average magni-

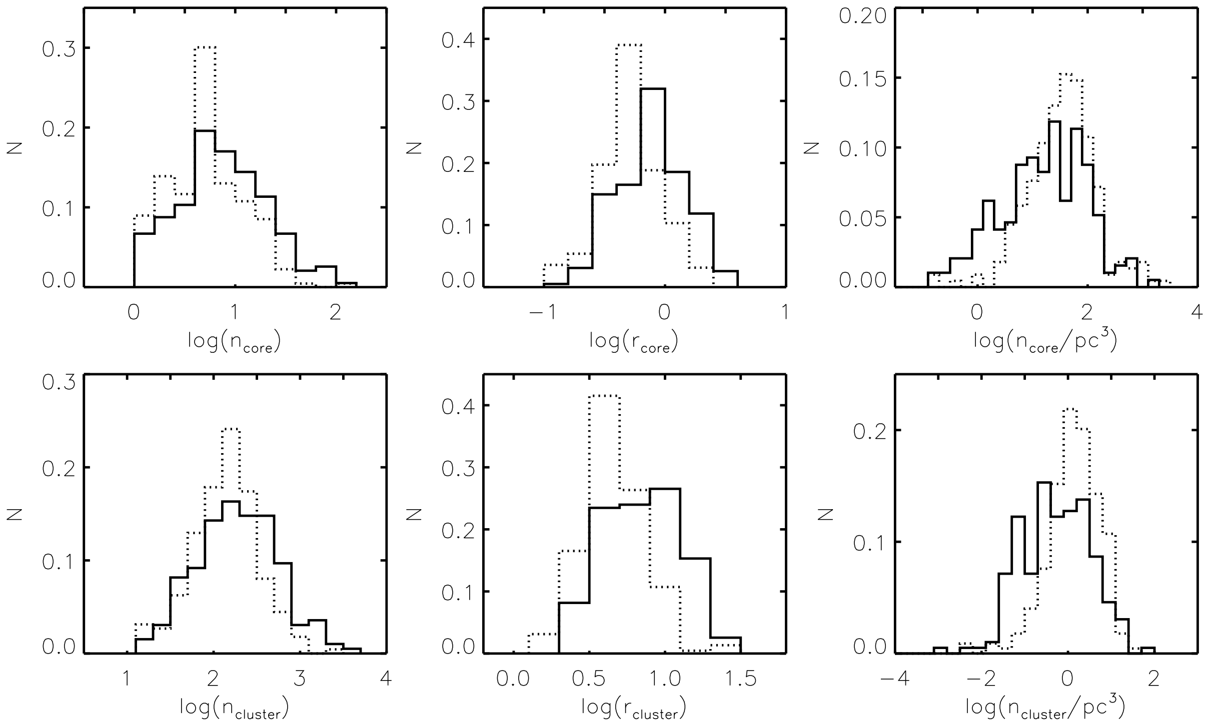

Figure 7. Distributions of logarithms of the number of stars in the clusters, of characteristic radii of the clusters in pc, and the number density of stars in the clusters in stars $\times$ pc^{-3} from left to right panels, respectively. The solid and dotted histograms result from the clusters hosting blue stragglers and those without blue stragglers, respectively.

tudes J, H, K_S of the clusters hosting blue stragglers are $-5.29 \pm 1.061, -5.71 \pm 0.984, -5.83 \pm 0.978$ whereas those of the clusters without blue stragglers are $-4.59 \pm 1.072, -4.78 \pm 1.019, -4.77 \pm 1.020$, respectively. That is, the clusters with blue stragglers are likely brighter than those without blue stragglers. Note that while the number of blue stragglers are correlated with the integrated luminosity of the host clusters, here we only concentrate on the presence of the blue straggler in a cluster regardless of the number of blue stragglers.

In Figure 7, we show distributions of logarithms of the number of stars in the clusters, of characteristic radii of the clusters in pc, and the number density of stars in the clusters in stars $\times$ pc^{-3} from left to right panels, respectively. Here we have calculated the size of a cluster using apparent angular radii of the core and the cluster provided by Kharchenko et al. (2012, 2013). Upper and lower panels result from core borders and cluster corona borders of the clusters, respectively. For instance, the upper-leftmost and lower-leftmost panels are due to the number of stars within the visible core radius and the visible total radius as defined by Kharchenko et al. (2012, 2013). According to Kharchenko et al. (2012, 2013), the visible core radius in degree corresponds to the distance from the cluster center where the slope of the radial density profile becomes flatter, and empirically it is less than King's core radius. The total visible radius of a cluster in degree is also defined as the distance from the cluster center where the surface density of stars becomes equal to the average density of the surrounding field (see also Piskunov et al. 2007).

On average, the core and total radii of the clusters with blue stragglers are larger than those without blue stragglers. Mean values of logarithms of the core radius and the total radius of clusters in pc hosting blue stragglers are -0.12 ± 0.095 and 0.85 ± 0.060 whereas those of the clusters without blue stragglers are -0.28 ± 0.071 and 0.66 ± 0.075, respectively. On the other hand, the number densities of the core and total clusters with blue stragglers appear smaller on average than those without blue stragglers. That is, mean values of logarithms of the number densities of the core and total clusters with blue stragglers are 1.19 ± 0.497 and -0.27 ± 0.600 whereas those of the clusters without blue stragglers are 1.53 ± 0.514 and 0.13 ± 0.606, respectively. Hence, it seems to suggest that blue stragglers form in larger and less dense clusters, regardless of the core or the total cluster. If this is the case, the total number of blue stragglers found in a given cluster does not have to correlate with the density (cf. Chatterjee et al. 2013). We note, in fact, that only a mild dependence of blue straggler frequency on the central density of the cluster has been reported so far (Piotto et al. 2004; Moretti et al. 2008). Instead of the density, as a measure of the compactness of the clusters, we take the ratio of the number density of the core to that of the total cluster. Interestingly enough, mean values of logarithms of the ratio of the number density of the cores to that of the total clusters with and without are 1.47 ± 0.201 and 1.39 ± 0.193, respectively, as shown in Figure 8. That is, in our view blue stragglers form in *condensed* clusters

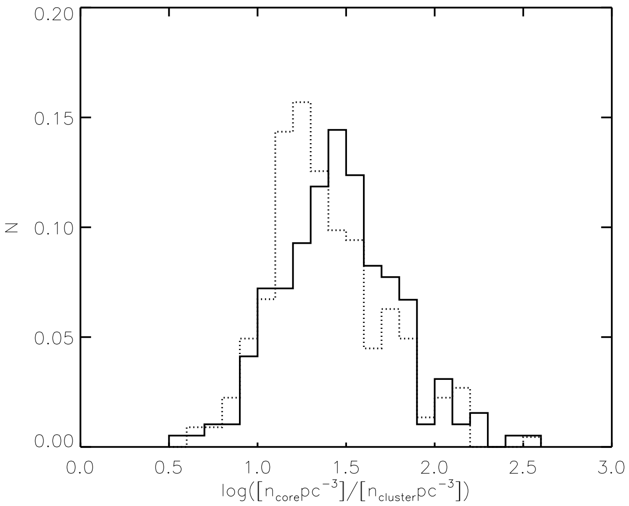

Figure 8. Distribution of logarithms of the ratio of cluster number density to core number density. The solid and dotted histograms result from the clusters hosting blue stragglers and those without blue stragglers, respectively.

rather than simply *dense* clusters. We consider this result can play a crucial role in considering blue straggler formation mechanisms.

4. Summary and Conclusions

Blue stragglers are unique species in the sense that explaining their presence and underlying phenomena requires complex interplay between stellar evolution and cluster dynamics. To understand the environments where blue stragglers are formed, in this paper we have explored properties of the Galactic open clusters by dividing the parent sample of the Galactic open cluster catalog (Ahumada & Lapasset 2007) into two subsample based on whether blue stragglers are found in the clusters, and statistically compare these two subsamples. We have taken advantage of the flag of yes-or-no, expecting that it is sufficient for clarifying the phenomenon of blue stragglers. This approach may be more plausible than studying correlations between blue straggler properties and properties of individual cluster, since the former is simple and easy to understand. As pointed out above, the latter demands a sophisticated process, often including heavy numerical simulations. We are aware that it is beyond the purposes of this paper to evaluate in details the dynamical and evolutionary properties of the open clusters within the Galactic environment. However, what we have found here are, at least, consistent with previously reported correlations and consequently should be regarded as a supplementary supporting evidence for a current view on the blue straggler formation mechanism. A physical mechanism of the generation of blue stragglers seems to be mass transfer in binary whose productivity is growing with time.

To sum up, we have found the following:

(1) Open clusters in which blue stragglers are present have a broader distribution with respect to the Z-axis than those in which blue stragglers are absent, such that the proportion of the clusters with blue stragglers are growing as moving further from the midplane of the Galaxy. Moreover, the probability that two distributions with respect to the Z-axis are drawn from the same distribution is 0.2%. It seems to suggest that open clusters need to be old enough to bear blue stragglers, in that open clusters located in the outer halo are relatively older than those in the midplane.

(2) Average values of $\log_{10}(t)$ of the clusters with blue stragglers and those without blue stragglers are 8.58 and 7.52, respectively.

(3) Averaged values of the colors $J-H$, $H-K_S$, $J-K_S$ of the clusters hosting blue stragglers are $0.43 \pm 0.170, 0.11 \pm 0.074, 0.54 \pm 0.235$ whereas those of the clusters without blue stragglers are $0.19 \pm 0.185, 0.09 \pm 0.084, 0.23 \pm 0.270$, respectively. The distribution of the clusters without blue stragglers can be fitted to the Poisson distribution with a sharp increase at the blue side, while the distribution of the clusters hosting blue stragglers appear to be a Gaussian.

(4) The clusters with blue stragglers are likely brighter than those without blue stragglers. The average magnitudes J, H, K_S of the clusters hosting blue stragglers are $-5.29 \pm 1.061, -5.71 \pm 0.984, -5.83 \pm 0.0978$ whereas those of the clusters without blue stragglers are $-4.59 \pm 1.072, -4.78 \pm 1.019, -4.77 \pm 1.020$, respectively.

(5) Apparently, blue stragglers form in larger and less dense clusters. As a result of investigating the ratio of the number density of the cores to that of the total clusters, however, we conclude that blue stragglers form in *condensed* clusters rather than simply *dense* clusters since mean values of logarithms of the ratio of the number density of the cores to that of the total clusters with and without are 1.47 ± 0.201 and 1.39 ± 0.193, respectively.

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