Exploring the Mass Segregation Effect of X-Ray Sources in Globular Clusters. III. Signs of Binary Disruption in M28

Zhongqun Cheng1, Huijun Mu2, Zhiyuan Li3,4, Xiaojie Xu3,4, Wei Wang1, and Xiandong Li3,4

1 School of Physics and Technology, Wuhan University, Wuhan 430072, People’s Republic of China; chengzq@whu.edu.cn
2 School of Physics and Microelectronics, Zhengzhou University, Zhengzhou 450001, People’s Republic of China
3 School of Astronomy and Space Science, Nanjing University, Nanjing 210023, People’s Republic of China
4 Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210023, People’s Republic of China

Abstract

Using archival Chandra observations with a total effective exposure of 323 ks, we derive an updated catalog of point sources in the bulge globular cluster M28. The catalog contains 502 X-ray sources within an area of \(\sim 475 \text{arcmin}^2\), and more than 90\% of these sources are first detected in this cluster. We find significant dips in the radial distribution profiles of X-ray sources in M28, and the projected distance and width of the distribution dip for bright \((L_X \gtrsim 4.5 \times 10^{36} \text{erg s}^{-1})\) X-ray sources are larger than for faint \((L_X \lesssim 4.5 \times 10^{30} \text{erg s}^{-1})\) sources. Fitting with the “generalized King model” gives a slightly larger average mass for the bright sources \((1.30 \pm 0.15 \, M_{\odot})\) than for the faint ones \((1.09 \pm 0.14 \, M_{\odot})\), which supports a universal delay in mass segregation between heavy objects in globular clusters. We show that the dynamical age of M28 is comparable to that of Terzan 5 and much smaller than that of 47 Tuc, but M28 is evolving faster (i.e., with a shorter two-body relaxation timescale) than 47 Tuc. These features may suggest an acceleration effect of cluster dynamical evolution by tidal shock in M28. Besides, we find an abnormal deficiency of X-ray sources in the central region \((R \lesssim 1.5)\) of M28 compared with its outskirts, which indicates that M28 may have suffered an early phase of primordial binary disruption within its central region, and the mass segregation effect will erase such a phenomenon as clusters evolve to an older dynamical age.

Unified Astronomy Thesaurus concepts: Globular star clusters (656); X-ray binary stars (1811); Stellar dynamics (1596); Dynamical friction (422); Tidal disruption (1696)

Supporting material: machine-readable table

1. Introduction

Globular clusters (GCs) are ancient self-gravitating systems in the universe, and their structure is subtly balanced by the production of energy in the core and the outflow of energy from the system until they evolve to final core-collapse (Hénon 1961). Two-body relaxation is the fundamental process driving cluster evolution, because it dominates the transportation of energy and mass in GCs. Through two-body relaxation, stars are driven to reach a state of energy equipartition. Lower-mass stars therefore tend to obtain energy and escape from the cluster (thus leading to the energy outflow in GCs), whereas main-sequence (MS) binaries and massive stars tend to lose energy and sink in the gravitational potential well of GCs, where strong dynamical interactions between binaries and other stars could take place frequently. Depending on the binary hardness (defined as \(\eta = |E_b|/E_k\), with \(E_b\) the bound energy of binaries and \(E_k\) the average stellar kinetic energy in GCs), soft binaries (\(\eta \ll 1\)) tend to absorb energy from fly-by stars and become softer or disrupted, whereas hard binaries (\(\eta \gtrsim 1\)) tend to transfer energy to fly-by stars and become harder (i.e., the binary burning processes; Heggie 1975; Hills 1975). Hard binaries can therefore strongly influence the evolution of GCs—sufficiently to delay, halt, or even reverse the core-collapse (Fregeau et al. 2003; Heggie & Hut 2003).

Theoretically, many products can be dynamically formed through the encounters of hard binaries in GCs, including intermediate-mass black holes (IMBHs; Miller & Hamilton 2002; Portegies Zwart & McMillan 2002; Gürkan et al. 2004; Portegies Zwart et al. 2004; Giersz et al. 2015; Fragione et al. 2018), binary compact objects that can contribute to gravitational wave sources (Portegies Zwart & McMillan 2000; Downing et al. 2010; Samsing et al. 2014; Rodriguez et al. 2015, 2016; Askar et al. 2017; Hong et al. 2018; Ye et al. 2020), low-mass X-ray binaries (LMXBs; Rasio et al. 2000; Ivanova et al. 2010; Giesler et al. 2018; Kremer et al. 2018a), millisecond pulsars (MSPs; Ivanova et al. 2008; Ye et al. 2019), cataclysmic variables (CVs; Ivanova et al. 2006; Shara & Hurley 2006; Belloni et al. 2016, 2017, 2019; Hong et al. 2017), coronally active binaries (ABs), and blue straggler stars (Fregeau et al. 2004; Chatterjee et al. 2013). As GCs age, it is natural to infer that more and more binary burning products are generated in their cores. However, not all of these products can be retained by the cluster, since hard binaries may receive a large recoil velocity and be ejected from the host cluster (Downing et al. 2011; Morscher et al. 2013, 2015; Bae et al. 2014; Kremer et al. 2018b).

At present, there is still no unambiguous evidence for IMBHs in Galactic GCs (Tremou et al. 2018; Abbate et al. 2019; Greene et al. 2019; Mann et al. 2019), while eight candidates for stellar-mass black holes (BHs) have been found in several GCs (Strader et al. 2012; Chomiuk et al. 2013; Miller-Jones et al. 2015; Bahramian et al. 2017; Giesers et al. 2018, 2019; Shishkovsky et al. 2018). For neutron star (NS) systems, about 21 NS-LMXBs (van den Berg 2020) and more
than 130 MSPs have been identified in Galactic GCs.\(^5\) For comparison, the abundances (i.e., number per unit stellar mass) of BH and NS systems are about 100–1000 times higher in GCs than in the Galactic field (Clark 1975; Katz 1975; Camilo & Rasio 2005; Ransom 2008; Generozov et al. 2018), which suggests that binary burning favors or assists the creation of these objects in GCs. However, when extending these studies to CVs and ABs, Cheng et al. (2018a) found that most GCs have a slightly lower X-ray emissivity (i.e., X-ray luminosity per unit stellar mass, which is a good proxy for CV and AB abundance in GCs) than the Galactic field, although the dynamical evolution of binaries is found to obey the Hills–Heggie law in GCs (Cheng et al. 2018b). This evidence suggests that, at least, the primordial binary formation channel of CVs and ABs is suppressed in most GCs.

A possible explanation is that the binary burning processes take place sequentially in GCs. Since the timescale for two-body relaxation is anticorrelated with the mass of the heavy object, stars with different masses are expected to sink to the cluster center with different speeds (i.e., there is a delay in mass segregation between different heavy objects in GCs). Therefore, with a larger average mass than normal stars, BHs and NSs are more likely to concentrate in the cluster center and take part in the binary burning processes, which lead to an overabundance of exotic BH and NS systems in GCs as compared to the Galactic field. Similar processes are inefficient for white dwarfs (WDs) due to their much smaller average mass. Moreover, progenitor MS binaries of CVs are more massive than WDs, and thus are more likely to concentrate in the cluster core and suffer strong dynamical encounters. Contrary to binary burning processes that transform MS binaries into CVs or ABs, simulations suggest that most of the primordial binaries will be dynamically disrupted in the cores of GCs (Davies 1997; Belloni et al. 2019).

The delay in mass segregation of heavy objects has been confirmed in two massive GCs, 47 Tuc and Terzan 5. Utilizing archival Chandra data, Cheng et al. (2019a, 2019b) performed a deep survey of weak X-ray sources in 47 Tuc and Terzan 5. They found significant dips in the surface density distribution profile of X-ray sources in these two clusters, with the locations (i.e., projected distance from the GC centers) and widths of the distribution dips for bright sources being larger than those for faint sources. The distribution dips are thought to be created by the mass segregation of heavy objects in GCs (Ferraro et al. 2012), while their different locations and widths may represent a delay in mass segregation between the considered objects. Indeed, the average mass of bright X-ray sources is estimated to be greater than that of faint sources, and thus they fall to the cluster center faster and their distribution dips will propagate outward further (Cheng et al. 2019a, 2019b). More interestingly, a comparison between these two clusters shows that the dynamical evolution of Terzan 5 is faster (i.e., with shorter two-body relaxation timescale), but its dynamical age is significantly less than that of 47 Tuc. Since Terzan 5 is located much closer to the Galactic center than 47 Tuc, these features may suggest that tidal stripping is effective in accelerating the dynamical evolution (and thus the binary burning processes) of GCs (Cheng et al. 2019a).

In this work, we perform a similar study of the mass segregation effect in X-ray sources in M28, focusing on revealing the dynamical disruption of binary stars in the cluster core. M28 is located in the inner Galactic region (\(l = 7^\circ 7982, b = -5^\circ 58068\)) at a distance of \(d = 5.5 \text{kpc}\) from the Sun (Harris 1996). The orbit of M28 was found to be highly eccentric, with perigalactic distance of \(R_p = 0.57 \pm 0.1 \text{kpc}\) and apogalactic distance of \(R_a = 2.9 \pm 0.23 \text{kpc}\) (Baumgardt et al. 2019), which indicates that M28 may have suffered strong tidal stripping in the Milky Way. The structure of M28 was found to be relatively compact, with a half-light radius of \(R_h = 1.97 \text{kpc}\) (corresponding to 3.15 pc) and a total mass of \(3.7 \times 10^5 \Msun\) (Harris 1996). On the other hand, M28 is found to host 12 MSPs (Bogdanov et al. 2011). This is the third largest population of known pulsars in GCs, after those of Terzan 5 (38) and 47 Tuc (25).\(^5\) These features make M28 a valuable laboratory for studying stellar dynamical interactions and cluster dynamical evolution.

The remainder of this paper is organized as follows. In Section 2, we describe the X-ray data analysis and creation of the catalog. We study the radial distribution of X-ray sources in Section 3, and explore its relation to mass segregation, Galactic tidal stripping, and binary dynamical evolution in Section 4. A brief summary of our main conclusions is presented in Section 5.

2. X-Ray Data Analysis

2.1. Chandra Observations and Data Preparation

So far, there are eight Chandra observations, all taken with the Advanced CCD Imaging Spectrometer (ACIS), with the aimpoint located at the S3 CCD. From the level 1 events file, we used the Chandra Interactive Analysis Observations (CIAO, version 4.11) and the Calibration Database (version 4.8.4) to reprocess the data, following the standard procedure.\(^6\) To inspect possible background flares, we also created a background light curve for each observation by excluding the source regions. A slight background flare was found in ObsID 2683; we therefore removed the episodes of background flares from this observation. The total effective exposure amounts to 323 ks in the central region of M28. We searched for X-ray sources within the field of view (FoV) of each observation, and utilized the ACIS Extract (AE; Broos et al. 2010) package to refine the source positions. Then, we corrected the relative astrometry among the X-ray observations. ObsID 9132, which has the longest exposure time, was adopted as the reference frame. Finally, we combined the eight observations into merged event files. Three groups of images have been created in soft (0.5–2 keV), hard (2–8 keV), and full (0.5–8 keV) bands and with bin sizes of 0.5, 1, and 2 pixels, respectively. As a demonstration, the merged full-band image (with bin size of 1 pixel) is illustrated in Figure 1. Our data preparation details are summarized in Table 1.

2.2. Source Detection and Sensitivity

Following the steps used for 47 Tuc and Terzan 5 (Cheng et al. 2019a, 2019b), we employed a two-stage approach to create the X-ray sources catalog in M28. First, we ran wavdetect on each of the nine combined images, using the “\(\sqrt{2}\) sequence” wavelet scales and aggressive false-positive probability thresholds to find weak X-ray sources. If possible X-ray sources were missed by the wavdetect script, we also

---

\(^5\) http://www.naic.edu/~pfreire/GCpsr.html

\(^6\) http://cxc.harvard.edu/ciao

---
Figure 1. Full-band (0.5–8 keV) Chandra merged image of M28. The images are smoothed with a Gaussian kernel with a radius of 3 pixels. The fields of view of the eight observations in Table 1 are shown as dashed boxes. Sources detected by Becker et al. (2003) are marked with red ellipses, while new detections of this work are shown as blue ellipses. The size of each ellipse represents $P_{\text{B}}$ being false. The size of each ellipse represents $P_{\text{B}}$ being false. Due to the much larger variation in detection sensitivity, only X-ray sources located within the field of view of ObsID 9132 and ObsID 9133 (green boxes) are used to calculate the surface density profile in Figure 3. A zoom-in view of the central 2' × 2' region (red square) is illustrated in the left panel of Figure 2. A gray dashed circle marks the half-light radius ($R_{\text{h}} = 1.97$) of M28.

inspected the merged images visually and added them to the detection source lists. The wadetect results were then combined into a master source list, which resulted in a candidate list of 576 sources. Owing to the relatively loose thresholds for source detection, this list was expected to include some false sources. Therefore, we utilized the AE package to extract and evaluate the properties of X-ray sources interactively and iteratively. AE provides an important parameter (i.e., the binomial no-source probability $P_{\text{B}}$) to evaluate the significance of a source, which is defined on the null hypothesis that a source does not exist in the source extraction aperture, and the observed excess number of counts over background is purely due to background fluctuations (Weisskopf et al. 2007).

The formula to calculate $P_{\text{B}}$ is

$$P_{\text{B}}(X \geq S) = \sum_{X=S}^{N} \frac{N!}{X!(N-X)!} p^X (1-p)^{N-X},$$

(1)

where $S$ and $B$ are the total numbers of counts in the source and background extraction region, $N = S + B$, and $p = 1/(1 + \text{BACKSCAL})$, with BACKSCAL being the area ratio of the background and source extraction regions. A larger $P_{\text{B}}$ value indicates that a source has a larger probability of being false.

When using AE we set a more stringent threshold value of $P_{\text{B}} > 0.001$ for invalid sources. As we found for 47 Tuc, this threshold $P_{\text{B}}$ value proved to be helpful in optimizing the source completeness and reliability. Then, by extracting, merging, pruning, and repositioning the candidate sources interactively and iteratively, we obtained a stable list in which all remaining sources meet the $P_{\text{B}}$ condition in either the full, soft, or hard band. Our final source catalog contains 502 X-ray sources. They are marked by ellipses in Figure 1 and the left panel of Figure 2. As a comparison, we also highlight the X-ray sources identified by Becker et al. (2003) as red ellipses in the figures. Due to the much shallower exposure (i.e., ~37 ks from ObsIDs 2683, 2684, and 2685) and smaller source search region ($R \leq 3'$), only 46 X-ray sources were detected in their work.

As suggested in Figure 1, the merged effective exposure maps of M28 are found to have a large variation within the Chandra FoV, which may lead to significant variation in detection sensitivity across the source analyzing region. Following the procedures employed for 47 Tuc (Cheng et al. 2019b), we utilized the merged event images to create maps of detection sensitivity. Briefly, we first masked out the source regions from the merged event files, and refilled them with the surrounding pixels. The source-free counts images were utilized to generate the background maps. Then, at each pixel of the survey field, we modeled its source and background areas with the local point-spread function (PSF; given by the averaged PSF maps weighted by exposure time) and BACKSCAL values (given by nearby sources from AE), which are used to estimate the background counts (B). With given BACKSCAL, B, and threshold $P_{\text{B}}$ value, we can derive limiting source counts (S) by solving Equation (1). Finally, we computed for each pixel the limiting detection count rates with the exposure map, and then converted them into limiting fluxes by assuming an absorption power-law model with photon index $\Gamma = 1.4$ and column density $N_{\text{H}} = 2.32 \times 10^{21} \text{cm}^{-2}$. Here $N_{\text{H}}$ is derived from the color excess $E(B - V)$ of M28 (Cheng et al. 2018a).
Table 1
Log of Chandra Observations

| ObsID | Date       | Exposure | R.A.     | Decl.     | Roll | Δx | Δy |
|-------|------------|----------|----------|-----------|------|----|----|
|       | (1)        | (2)      | (3)      | (4)       | (5)  | (6) | (7) | (8) |
| 2683  | 2002 Sep 9 | 10.87    | 276.1237 | −24.8904  | 273.16 | 0.045 | −0.254 |
| 2684  | 2002 Jul 4 | 12.74    | 276.1376 | −24.8900  | 285.35 | 0.284 | −0.252 |
| 2685  | 2002 Aug 4 | 13.51    | 276.1333 | −24.8904  | 274.68 | 0.381 | −0.268 |
| 9132  | 2008 Aug 7 | 142.25   | 276.1416 | −24.8904  | 274.46 | 0.000 | 0.000 |
| 9133  | 2008 Aug 10| 54.45    | 276.1416 | −24.8904  | 274.31 | −0.041 | −0.296 |
| 16748 | 2015 May 30| 29.65    | 276.1342 | −24.8651  | 79.66  | 0.338 | 0.231 |
| 16749 | 2015 Aug 7 | 29.55    | 276.1412 | −24.8738  | 274.53 | −0.093 | −1.044 |
| 16750 | 2015 Aug 11| 29.56    | 276.1410 | −24.8740  | 274.41 | 1.271 | −0.341 |

Note. Columns (1)–(3): Chandra observation ID, date, and effective exposure time. Columns (4)–(6): optical pointing positions of the telescope and the roll angle of each observation. Columns (8) and (9): shift in R.A. and decl.

2.3. Catalog of Sources

For the 502 sources in the catalog, we extracted their X-ray photometry and spectra with AE. The default source aperture was defined to enclose a PSF power fraction of ~90%, which was allowed to reduce to a minimum value of ~40% for very crowded sources. We built background regions with the AE “BETTER_BACKGROUNDS” algorithm, and their scales were set to enclose at least a minimum of 100 background counts through the AE “ADJUST BACKSCAL” stage. We computed the net source counts in each of the soft, hard, and full bands. Among the 502 X-ray sources, we found that about one-third (i.e., 177/502) of them have net counts greater than ~30 in the full band. Using the AE automated spectral fitting script, we modeled their spectra with an absorbed power-law spectrum; the photon index was set as a free parameter and the unabsorbed energy was allowed to reduce to a minimum value of ∼90%, which was de ned to enclose a PSF power fraction of 1/8. Among the 502 X-ray sources, we also computed for each source a projected photon index Δ, which is constrained to be no less than $N_H = 2.32 \times 10^{21}$ cm$^{-2}$. For sources with net counts less than ~30, we converted their net count rates into unabsorbed energy fluxes using a power-law model. During the conversion, we fixed the photon index at $\Gamma = 1.4$ and froze the absorption column density at $N_H = 2.32 \times 10^{21}$ cm$^{-2}$. Adopted the AE-generated merged spectral response files to calibrate the flux estimation.

Finally, we collated the source extraction and spectral fitting results into a main X-ray source catalog, with source labels sorted by their R.A. Assuming a distance of 5.5 kpc for M28 (Harris 1996), we calculated for each X-ray source an unabsorbed luminosity in each of the soft, hard, and full bands. By adopting an optical central coordinate $\alpha = 18^h24^m32^s73$ and $\delta = -24^\circ52^\prime31^\farcs07$ for M28 (Micocchi et al. 2013), we also computed for each source a projected distance from the cluster center. The final catalog of point sources is presented in Table 2.

3. Analysis: Source Radial Distribution

Before the analysis of the surface density distribution of X-ray sources in M28, we first check the source detection sensitivity across the merged Chandra FoV. Due to the large difference in exposure time between ObsID 9132/9133 and other observations (Table 1), the variation in limiting detection sensitivity is found to be over one order of magnitude. To minimize the uncertainty, we choose the FoV of ObsID 9132/9133 (green boxes in Figure 1) as the analyzing region for the radial distribution of X-ray sources in this paper; it has a deep and relatively flat detection sensitivity. The limiting detection sensitivity of the FoV of ObsID 9132/9133 is illustrated as a function of cluster projected radius in the right panel of Figure 2, with the red, green, and blue solid lines represent the median, minimum, and maximum detection limits at each radial bin, respectively. For comparison, we also display the photon flux of each source sample as a black cross in the figure. It is evident that almost all of the X-ray sources are located above the minimum sensitivity line. Due to the constraint of the FoV of ObsID 9132/9133, the coverage factor $f$ (defined as $\Delta A/2\pi dr$, with $2\pi dr$ being the area of cluster radial bins and $\Delta A$ the corresponding coverage area of the FoV of ObsID 9132/9133) is less than 1 at larger cluster radii. We multiplied $f$ by $10^{-4}$ and plot it as purple dashed line in the figure.

A total of 467 X-ray sources are selected within the FoV of ObsID 9132/9133 (also with $R < 10'$); we plot their surface density profile as black dots in Figure 3(a). Compared with a King model profile that describes the radial surface density distribution of normal stars in GCs, we found that the distribution profile of X-ray sources in M28 decreases rapidly outside the cluster core radius, then reaches a plateau at $1' < R < 3'$, and there is a distribution dip around $R ∼ 0'/6$ (see also the source distribution in the right panel of Figure 3). According to Cheng et al. (2019a, 2019b), such a distribution dip could be caused by mass segregation of X-ray sources in GCs. Since the mass segregation effect is found to be luminosity-dependent in 47 Tuc and Terzan 5, we also divided the source sample into two subgroups according to their X-ray luminosities. To balance the source counts between the two groups of samples, we set a threshold photon flux of $F_X = 3.0 \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$ (or luminosity of $L_X \sim 4.5 \times 10^{33}$ erg s$^{-1}$) and obtained 220 and 247 sources for the faint and bright groups of X-ray sources separately. The surface density profiles of the faint and bright groups of X-ray sources are plotted as black dots in Figures 3(b) and (c), respectively. Again, significant distribution dips also can be found for these two subgroups of X-ray sources.

Due to source blending, the source density is more or less underestimated in the cluster center. Assuming that a faint source could be easily blended with nearby brighter sources when it is located within the source extraction regions of the latter, we also corrected for the blending effect in the central region of M28. For each concentric annulus of area $A_{ann}$, the number of blended sources can be roughly estimated by the
function

\[ N_b(>F_p) = N_X(>F_p)\beta, \]  

(2)

where \( N_X(>F_p) \) is the number of bright X-ray sources (with photon flux greater than \( F_p \)) located within \( A_{\mathrm{ann}} \), and \( \beta = A_{\mathrm{tot}}/A_{\mathrm{ann}} \), with \( A_{\mathrm{tot}} \) being the total extraction regions of the bright X-ray sources. The distribution profiles of the blended sources are presented as purple pluses in Figure 3. We estimated that about four GC sources are blended in M28, with about three (one) of them belonging to the faint (bright) group of X-ray sources.

To identify the possible signal of mass segregation of X-ray sources in M28, we modeled the X-ray source distribution profiles with several components. Following the procedures employed in 47 Tuc and Terzan 5 (Cheng et al. 2019a, 2019b), we adopted the \( \log N - \log S \) relations determined by Kim et al. (2007) to estimate the contribution of the cosmic X-ray background (CXB) sources in the FoV. The cumulative number count of CXB sources above a limiting sensitivity flux \( S \) can be estimated with the function

\[ N_{\mathrm{CXB}}(>S) = 2433(S/10^{-15})^{-0.64} - 186 \text{ deg}^{-2}. \]  

(3)

This equation is derived from Equation (5) of Kim et al. (2007) by assuming a photon index of \( \Gamma = 1.4 \) for the Chandra ACIS observations in the 0.5–8 keV band. With the maps of limiting sensitivity obtained in Section 2.2, we calculated the CXB contributions and plot them as black dotted lines in Figure 3.

Since M28 is located very close to the Galactic center, the contamination from Galactic bulge and disk X-ray sources is non-negligible, as is the case in Terzan 5. Such a contamination also can be noticed in Figure 3, where the observed X-ray sources significantly exceed the predicted CXB components at large cluster radius. According to Miocchi et al. (2013), the surface density distribution of normal stars in M28 is dominant over the Galactic background stars within \( R \sim 7'' \). Therefore, we can estimate the Galactic background components by looking at the distribution profiles of X-ray sources outside \( R \sim 7'' \). Assuming a uniform spatial distribution for the Galactic bulge and disk X-ray sources within the Chandra FoV, we calculated the Galactic background components \( (N_G) \) with the limiting sensitivity map obtained in Section 2.2; these were normalized to match the surface density profiles of X-ray sources beyond \( R \sim 7'' \). The sum of the CXB and Galactic background components is shown as blue dashed lines in Figure 3. Then, the excess of X-ray sources over the blue dashed lines can be reasonably attributed to the GC X-ray sources (i.e., \( N_X + N_B - N_{\mathrm{CXB}} - N_G \)). Among the 467 X-ray sources, we found that \( \sim 215 \) of them are from M28, with about 125 (90) belonging to the faint (bright) group.

To better compare the radial distribution of X-ray sources with normal stars in M28, we plot the best-fitting King model profiles of M28 as green solid lines in Figure 3. The best King model profiles were calculated with the cluster concentration \( (c = 2.01) \) and the core radius \( (R_c = 10''5) \); Miocchi et al. (2013); we normalized them to match the number of GC X-ray sources for each group of samples. The sum of the CXB component \( (N_{\mathrm{CXB}}) \), Galactic background component \( (N_G) \), and King model component \( (N_K) \) is shown as red solid lines in the figure. From Figure 3, it can be observed that there are significant differences

\[ \text{(3)} \]
between the distribution profiles of observed X-ray sources ($N_X$) and model-predicted sources in M28. We calculated their residuals with the equation $N_X + N_B - N_{\text{CXB}} - N_G - N_K$, and these are illustrated as a function of $R$ in the lower panels of Figure 3. As shown in the figure, there is a slight excess of X-ray sources over the model predictions in the core region of M28, which decreases to a minimum value at the distribution dip and then increases again at larger cluster radii. Following the methods used for Terzan 5 (Cheng et al. 2019a), we estimated the significance of the distribution dips with the function $S/N = (N_{\text{CXB}} + N_B + N_K - N_X - N_B)/\sqrt{N_{\text{CXB}}^2 + N_G^2 + N_K^2 + N_{\text{CXB}}^2 + N_B^2 + N_K^2 + N_G^2 + N_K^2}(1 + \beta^2)$. By adopting a nominal fitting error of $\sigma_G = 5\%$ for the King model fitting and Galactic background estimation, a CXB variance of $\sigma_r = 17\%$ for the Chandra source analyzing region in M28 (Moretti et al. 2009), and the Poisson uncertainties $\sigma_{\text{fl}}$ estimated with the formulae of Gehrels (1986) for detected X-ray sources, we adjusted the ranges of the distribution dips and estimated a maximum significance for each group of X-ray sources. The parameters of the distribution dips are summarized in Table 3, and their maximum significance values are indicated by black text in the lower panels of Figure 3. We found that the median locations and widths (i.e., ranges of $N_X + N_B - N_{\text{CXB}} + N_G + N_K$) of the distribution dips for the total, faint, and bright groups of X-ray sources are $R_{\text{dip}} \simeq 45''$, $\Delta R_{\text{dip}} \simeq 75''$, $R_{\text{dip}} \simeq 35''$, $\Delta R_{\text{dip}} \simeq 60''$, and $R_{\text{dip}} \simeq 65''$, $\Delta R_{\text{dip}} \simeq 110''$, respectively.

Beside the distribution dips, it can be seen from Figure 3 that there are significant distribution bumps of X-ray sources in the outskirts of M28. Contrary to the traditional idea that GC X-ray sources are concentrated and abundant in the cluster center, these features may suggest an overabundance of X-ray sources in the outskirts of M28. To quantify this phenomenon, we divided the survey area into several concentric annuli, and defined in each annulus the relative abundance ratio of X-ray sources as

$$R_X = (N_X + N_B - N_{\text{CXB}} - N_G)/N_X.$$  

$R_X > 1$ ($R_X < 1$) indicates that there is a relative overabundance (deficiency) of X-ray sources in the annulus region. In Table 3, we calculated $R_X$ in several radial bins in M28. It is evident that the relative abundance of X-ray sources is $\sim 150\%$ larger than the prediction for normal stars within the cluster core. However, this excess (i.e., $N_X + N_B - N_{\text{CXB}} - N_G - N_K \simeq 11$ within $R < 10''$) cannot compensate for the number of sources missed in the distribution dip (i.e., with $N_X + N_B - N_{\text{CXB}} - N_G - N_K \simeq -74$ within $10'' \ll R \ll 90''$), and there is an abnormal deficiency of X-ray sources in the central region (i.e., $R_X \sim 60\%$ within $R \lesssim 90''$) of M28 compared to its outskirts (i.e., $R_X \sim 200\%$ at $R \gtrsim 90''$).

4. Discussion

4.1. Mass Segregation of X-Ray Sources in M28

According to Figure 3, the locations and widths of the distribution dips for bright X-ray sources are clearly larger than for faint X-ray sources, which may suggest a delay in mass segregation between these two groups in M28. Similar to the procedures outlined for 47 Tuc and Terzan 5 (Cheng et al. 2019a, 2019b), we estimated an average mass for each group of X-ray sources by fitting the surface density distribution with the “generalized King model.” This model assumes that all stars are dynamically relaxed in the cluster, and thus the radial distribution of more massive objects (such as X-ray sources) will be more centrally concentrated than that of the reference normal stars. To ensure that the selected sources are not biased by detection sensitivity and are dynamically relaxed in M28, we set a minimum threshold photon flux of $8 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ for the faint group of X-ray sources and constrain the source analyzing region to be $R \leq 30''$ (i.e., source samples selected by the red and orange dotted boxes in the right panel of Figure 2). We then corrected background contamination and the blending effect for each group of X-ray sources and we plot their cumulative distributions as solid step lines in Figure 4(a). According to the generalized King model, the projected surface density profile of heavy objects can be expressed as

$$S(R) = S_0 \left[ 1 + \left( \frac{R}{R_c} \right)^{2(1-3q)/2} \right].$$  

Table 2

Main Chandra Source Catalog

| XID      | R.A.  | Decl. | Error (arcsec) | $R$ (arcsec) | log $P_{\text{fl}}$ | $C_{\text{net}/0}$ (counts) | $C_{\text{net}/0}$ (photons s$^{-1}$ cm$^{-2}$) | $F_{\text{net}/0}$ (photons s$^{-1}$ cm$^{-2}$) | $F_{\text{net}/c}$ (erg s$^{-1}$) | log $L_{\text{X,c}}$ (erg s$^{-1}$) |
|----------|-------|-------|----------------|-------------|-------------------|-----------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
|          |       |       |                |             |                   |                             |                                         |                                        |                                   |                                |
| 1        | 275.886925 | $-$24.816634 | 0.6           | $-$837.5     | $<5$              | $108^{+134}_{-43}$          | $38^{+57}_{-20}$                        | $2.52E-6$                          | $9.94E-7$                      | $31.58$                        | $31.42$                        |
| 2        | 275.896753 | $-$24.885806 | 0.5           | $783.8$      | $<5$              | $154^{+170}_{-67}$          | $67^{+84}_{-36}$                        | $3.49E-6$                          | $1.71E-6$                      | $31.69$                        | $31.55$                        |
| 3        | 275.901918 | $-$24.892048 | 0.5           | $769.7$      | $<5$              | $207^{+139}_{-79}$          | $79^{+96}_{-62}$                        | $4.91E-6$                          | $2.11E-6$                      | $31.80$                        | $31.62$                        |
| 4        | 275.912525 | $-$24.037327 | 0.6           | $923.8$      | $<5$              | $225^{+249}_{-78}$          | $78^{+96}_{-61}$                        | $6.98E-6$                          | $2.71E-6$                      | $32.11$                        | $31.76$                        |
| 5        | 275.928294 | $-$24.834271 | 0.6           | $692.0$      | $<5$              | $76^{+29}_{-10}$            | $10^{+19}_{-7}$                         | $1.88E-6$                          | $2.74E-7$                      | $31.46$                        | $31.30$                        |
| 6        | 275.937572 | $-$24.977005 | 0.5           | $754.2$      | $<5$              | $138^{+139}_{-59}$          | $59^{+45}_{-24}$                        | $3.12E-6$                          | $1.49E-6$                      | $31.61$                        | $31.43$                        |
| 7        | 275.940597 | $-$24.837490 | 0.3           | $650.3$      | $<5$              | $364^{+341}_{-201}$        | $210^{+225}_{-184}$                    | $7.99E-6$                          | $4.89E-6$                      | $32.15$                        | $32.04$                        |
| 8        | 275.945923 | $-$24.992580 | 0.3           | $761.8$      | $<5$              | $461^{+435}_{-230}$        | $207^{+219}_{-169}$                    | $1.21E-5$                          | $6.05E-6$                      | $32.25$                        | $32.09$                        |

Note. Column (1): sequence number of the X-ray source catalog, sorted by R.A. Columns (2) and (3): R.A. and decl. for epoch J2000.0. Columns (4) and (5): estimated standard deviation of the source position error and its projected distance from cluster center. Column (6): logarithmic Poisson probability of a detection not being a source. Columns (7)–(10): net source counts and photon flux extracted in the full (0.5–8 keV) and hard (2–8 keV) bands. Columns (11) and (12): unabsorbed source luminosity in full and hard bands. The full content of this table is available online.

(This table is available in its entirety in machine-readable form.)
Here, $S_0$ is the normalization constant, and $q = M/M_*$ is the average mass ratio of heavy objects to the reference normal stars. $R_c = 10.5''$ is the cluster core radius of M28, which was determined by stars over the red giant branch/subgiant branch/turn-off point or the upper main sequence (Miocchi et al. 2013).

For comparison, we also illustrate the cumulative radial distribution of MSPs as the blue step line in Figure 4(a). Among all the considered objects, MSPs show the highest degree of central concentration, followed by the bright and faint groups of X-ray sources, and the reference normal stars. Using a maximum-likelihood method, we fit the cumulative radial distributions of the heavy objects with Equation (5), which yields mass ratios of $q = 2.38 \pm 0.35$, $q = 1.85 \pm 0.22$, and $q = 1.55 \pm 0.20$ for MSPs, and bright and faint X-ray sources, respectively.\footnote{Here the errors are quoted at the 1$\sigma$ level.} Assuming that the dominant visible stellar population has a mass of $M_* \sim 0.7 M_\odot$ in M28 (Becker et al. 2003), we derived average masses of $1.67 \pm 0.25 M_\odot$, $1.30 \pm 0.15 M_\odot$, and $1.09 \pm 0.14 M_\odot$ for MSPs, and the bright and faint groups of X-ray sources, respectively. The best “generalized King model” fitting results are shown as dotted lines in Figure 4(a). The average mass of the bright group of X-ray sources is slightly larger than that of the faint group, which is consistent with the observed distribution dips in M28. In other words, the bright X-ray sources are more massive and their two-body relaxation timescale is shorter, thus they are expected to fall to the cluster center faster and their distribution dip will propagate outward further in M28. We found that the delay in segregation of X-ray sources in M28 is consistent with that found in 47 Tuc and Terzan 5 (Cheng et al. 2019a, 2019b), supporting a universal mass segregation effect for X-ray sources in GCs.

4.2. Acceleration of GC Dynamical Evolution by Tidal Stripping

As suggested by Ferraro et al. (2012), the mass segregation effect of heavy objects can be used to build a “clock” to measure the dynamical evolution age of GCs, and GCs with a larger projected radius of distribution dips (i.e., $R_{\text{dip}}$ in units of cluster core radius) are thought to be dynamically older. In Figure 3, we found that the projected radius of the distribution dip for bright and faint groups of X-ray sources is $R_{\text{dip}} \approx 60'' \approx 5.7 R_c$ and $R_{\text{dip}} \approx 35'' \approx 3.3 R_c$ separately. At first sight, values of $R_{\text{dip}}$ in M28 are smaller than those detected in 47 Tuc and Terzan 5 (i.e., with $R_{\text{dip}} \approx 8.2 R_c$ and $R_{\text{dip}} \approx 7.8 R_c$ for the bright sources, $R_{\text{dip}} \approx 4.8 R_c$ and $R_{\text{dip}} \approx 3.9 R_c$ for the faint sources, respectively; Cheng et al. 2019a), which suggests that M28 is dynamically younger than Terzan 5 and 47 Tuc. However, the precision of $R_{\text{dip}}$ is subject to the binning of the heavy objects, which may hamper the comparison of dynamical age between GCs. Therefore, we also estimated the dynamical age of M28 with the $A^+$ indicator, which is defined as the area enclosed between the cumulative radial distribution of heavy objects (here the X-ray sources $\phi_X(R)$) and that of reference stars ($\phi_{\text{REF}}(R)$):

$$A^+(R) = \int_{R_0}^R (\phi_X(R) - \phi_{\text{REF}}(R)) \, dR.$$ (6)
As stated by Alessandrini et al. (2016), the $A^+$ indicator is binning-independent and more precise than $R_{\text{disp}}$, and it can be applied to all GCs (Lanzi et al. 2016; Ferraro et al. 2018).

In Figure 4(b), we assess the dynamical age of M28 with the $A^+_{\text{h}}$ indicator, by integrating the value of $A^+$ from the cluster center to the half-light radius. For comparison, the data for Terzan 5 and 47 Tuc are also illustrated in the figure; they are adopted from Cheng et al. (2019). Considering that the mass segregation effect is luminosity-dependent in M28, we first set a minimum threshold unabsorbed luminosity of $L_X \gtrsim 5.0 \times 10^{30} \text{erg s}^{-1}$ for the X-ray source sample (i.e., the same as in Terzan 5 and 47 Tuc). Then, we corrected the source blending and background contamination for the source sample, and plot their cumulative radial distribution as the blue solid step line in Figure 4(b). As in Terzan 5 and 47 Tuc, we adopted the King model to calculate the distribution of reference normal stars in M28, and this is plotted as blue dotted line in the figure. The integration yields a dynamical age of $A^+_{\text{h}} = 0.13$ for M28, which is comparable to that for Terzan 5 ($A^+_{\text{h}} = 0.14$) but much smaller than that for 47 Tuc ($A^+_{\text{h}} = 0.19$). Again, the smallest value of $A^+_{\text{h}}$ indicates that M28 is dynamically the youngest among the three GCs.

However, the above suggestion is challenged by the other dynamical age indicator. With a shorter core relaxation timescale in M28 ($t_{\text{relax}} = 7.62$) than in 47 Tuc (i.e., $t_{\text{relax}} = 7.84$; Harris 1996), M28 is expected to evolve faster and it should be dynamically older than 47 Tuc. Indeed, considering that the age of M28 ($\tau \sim 12.5\text{--}13.0 \text{Gyr}$; Kerber et al. 2018) is comparable to that of 47 Tuc ($\tau \sim 13.06 \text{Gyr}$; Forbes & Bridges 2010), we can infer that the dynamical age of M28 ($\tau_{\text{relax}} \sim 300$) is larger than that of 47 Tuc ($\tau_{\text{relax}} \sim 190$). Obviously, these results are in conflict with what $R_{\text{disp}}$ and $A^+_{\text{h}}$ suggest.

A possible explanation is that M28 may have experienced stronger tidal stripping in the Milky Way, as discussed in the case of Terzan 5 (Cheng et al. 2019). The orbit of M28 is short and highly eccentric, with perigalactic distance $R_p = 0.57 \pm 0.1 \text{ kpc}$ and apogalactic distance $R_a = 2.9 \pm 0.23 \text{ kpc}$, which is much closer to the Galactic center than 47 Tuc (with $R_a = 5.46 \pm 0.01 \text{ kpc}$, $R_a = 7.44 \pm 0.00 \text{ kpc}$; Baumgardt et al. 2019). Accordingly, M28 will suffer from a stronger tidal shock in the Galactic field, which accelerates the evaporation rate of stars (and thus increases the rate of energy outflow) from the cluster. In response, the cluster will contract homologically, to increase the stellar density and enhance the energy production rate of the cluster core. In fact, although the total mass of M28 ($M_{\text{tot}} \sim 3.7 \times 10^5 M_\odot$) is about a third of that of 47 Tuc ($M_{\text{tot}} \sim 1.2 \times 10^6 M_\odot$; Cheng et al. 2018), we found that its structure is more compact, its cluster central luminosity density ($\rho \sim 10^{4.86} L_\odot \text{pc}^{-3}$) is comparable to that of 47 Tuc ($\rho \sim 10^{4.88} L_\odot \text{pc}^{-3}$; Harris 1996), and its specific stellar encounter rate ($\gamma \sim 1.2 \times 10^{22} \text{yr}^{-1}$) is clearly larger than that of 47 Tuc ($\gamma \sim 2 \times 10^{22} \text{yr}^{-1}$; Cheng et al. 2018). Taking these aspects together, we argue that M28 is very similar to Terzan 5: they have both suffered from strong tidal stripping in the Galactic field, and the tidal shock is efficient in accelerating their dynamical evolution.

### 4.3. Mass Segregation and Disruption of Binary Stars in GCs

In Section 3 we show that there is an abnormal deficiency of X-ray sources in the central region of M28 compared with its outskirts (Table 3). Such a phenomenon is challenging to our current knowledge of the X-ray source distribution in GCs, which holds that X-ray sources are concentrated in the cluster center, and their abundance is greater in the central region than in the outskirts of GCs. According to Cheng et al. (2019), there are two formation channels for X-ray sources in GCs. The first is the dynamical channel, which is dominant in the cluster core and may be responsible for the formation of exotic objects (i.e., LMXBs, MSPs, etc.) and bright CVs in GCs (Pooley 2003; Pooley & Hut 2006). The other is the primordial binary channel, which prevails in the outskirts of GCs and is a significant contributor to the population of weak X-ray sources (i.e., faint CVs and ABs) in GCs (Cheng et al. 2018a, 2019b). Simulations suggest that the primordial binary channel is suppressed compared with the dynamical channel in the cluster center, since most of the primordial binaries will be dynamically disrupted before they can evolve into weak X-ray sources in the dense core of GCs (Davies 1997; Cheng et al. 2018a; Belloni et al. 2019). If this were the case, the abnormal deficiency of X-ray sources in the central region of M28 may represent a relic of early primordial binary disruption in the center of GCs.

In fact, we also found in the literature that there are similar peculiar radial distributions of MS binaries in star clusters. For example, by searching the F-star binary systems in the

| Source Groups | $R$ (2) | $N_c$ (3) | $N_b$ (4) | $N_{\text{CXB}}$ (5) | $N_{\text{G}}$ (6) | $N_{\text{F}}$ (7) | Ratio (8) |
|---------------|--------|----------|----------|-----------------|-----------------|-----------------|----------|
| All Sources   | 16–47  | 19        | 0.14     | 2.80            | 2.38            | 72.79           | 8.96     |
| Faint Sources | 16–47  | 10        | 0.11     | 1.84            | 1.66            | 45.24           | 7.96     |
| Bright Sources| 13–53  | 10        | 0.03     | 1.29            | 1.09            | 34.51           | 5.81     |

### Table 3

X-Ray Source Distribution Features in M28

#### Note.

Column (1): name of the source groups defined in Figure 3. Column (2): the ranges (in units of arcseconds) of the annular regions. Columns (3)–(7): number of detected X-ray sources, possible count of blended sources, CXB sources, Galactic background sources, and sources predicted by the King model within the annular region. Column (8): the maximum signal-to-noise ratio (i.e., $(N_{\text{CXB}} + N_c - N_b - N_{\text{G}})/\sqrt{N_{\text{CXB}}^2 + N_c^2 + N_b^2 - 2 N_{\text{CXB}} N_c - 2 N_{\text{CXB}} N_b - 2 N_c N_b (1 + 2b^2)}$) of the distribution dip and the relative abundance ratio (i.e., $(N_c + N_b - N_{\text{CXB}} - N_{\text{G}})/N_c$) of X-ray sources in the annular region.

The Astrophysical Journal, 892:16 (11pp), 2020 March 20

Cheng et al.
Traditionally, the BH subcluster was thought to be decoupled from the rest of the cluster and would lead to the ejection of most BHs on a timescale of a few gigayears (Kulkarni et al. 1993; Sigurdsson & Hernquist 1993). However, modern state-of-the-art simulations of GCs indicate that the BH subcluster does not stay decoupled from the rest of GC for prolonged periods, since interactions that eject BHs from the subcluster also cause it to expand and recouple with the host cluster, which dramatically increases the timescale for BH evaporation (Breen & Heggie 2013; Morscher et al. 2013, 2015; Wang et al. 2016; Kremer et al. 2019a).

Nevertheless, recent simulations of GCs have shown that more massive objects (such as stellar-mass BHs) may play a fundamental role in driving the evolution of clusters and shaping their present-day structure (Chatterjee et al. 2017; Arca Sedda et al. 2018; Askar et al. 2018; Weatherford et al. 2018; Kremer et al. 2019b). Under the effect of mass segregation, BHs are expected to concentrate to the cluster center and form a high-density subcluster (Spitzer 1969), which may influence the dynamical evolution of primordial binaries in two ways. First, the BH subcluster may quench or slow down the mass segregation of binaries in GCs (Weatherford et al. 2018), and compared to clusters with few BHs, GCs with a large number of BHs are found to have a large core radius and low central density (thus longer two-body relaxation timescale; Merritt et al. 2004; Hurley 2007; Chatterjee et al. 2017; Arca Sedda et al. 2018; Askar et al. 2018). Second, the BH subcluster may serve as a dominant internal energy source and suppress any other binary burning processes in GCs. For example, simulations show that the binary burning processes of NSs are suppressed by BHs in GCs, and the number of dynamically formed MSPs is anticorrelated with the population of BHs retained in the host cluster (Ye et al. 2019). Therefore, primordial binaries will either be disrupted or be transformed (i.e., through exchange encounters) into BH–MS binaries when they sink into the BH subcluster, and their evolution (both dynamical and primordial channels) to CVs or ABs will be suppressed in the central region of GCs. Taking these aspects together, we argued that it is possible to have a long-lived abnormal deficiency of weak X-ray sources in the central region of a cluster compared with its outskirts.

Although the BH subcluster may play an important role in creating and maintaining the peculiar radial distribution of X-ray sources in M28, we argue that the population of retained BHs in this cluster is small. This is because of not only the large population of MSPs, but also the apparent mass segregation effect of X-ray sources that is found in this cluster. Indeed, we found in Section 3 that there is a slight excess of X-ray sources in the core region of M28, which suggests that M28 may have exhausted its BH population, thus NS and low-mass binaries started to fall into the cluster core and dominate the binary burning processes. If this were the case, the mass

\[ A_{\text{BH}} = \frac{M_{\text{BH}}}{M_{\text{tot}}} \]

of BHs is calculated with Equation (6), which is a good indicator of cluster dynamical age.
segregation effect would gradually erase the deficiency of X-ray sources in the central region of M28. In fact, with a larger dynamical age than M28, we found that the deficiency of X-ray sources in the central region of Terzan 5 is not as serious as in M28 (Cheng et al. 2019a). While 47 Tuc has a much older dynamical age than M28 and Terzan 5, most of its X-ray sources are concentrated in the cluster center, and their relative abundance ratio in the core region is much larger than that in the cluster outskirts (Cheng et al. 2019b).

5. Summary

We have presented a sensitive study of weak X-ray sources in M28. By analyzing the radial properties of X-ray sources in this cluster, our main findings are as follows.

1. We detected 502 faint X-ray sources within an area of ~475 arcmin$^2$ in M28. The cleaned net exposure time of the study is 232 ks, and more than 90% of the sources are first detected in this cluster.

2. We found significant distribution dips in the surface density distribution profiles of X-ray sources in M28. The location and width of the distribution dips for the total, faint ($L_X < 4.5 \times 10^{30}$ erg s$^{-1}$), and bright ($L_X > 4.5 \times 10^{30}$ erg s$^{-1}$) source samples are $R \sim 45''$, $\Delta R \sim 75''$, $R \sim 35''$, $\Delta R \sim 60''$, and $R \sim 65''$, $\Delta R \sim 110''$, respectively. There is a delay in mass segregation between the faint and bright groups of X-ray sources in M28.

3. The “generalized King model” fitting yields a larger average mass for the bright group of X-ray sources (1.30 ± 0.15 $M_\odot$) than for the faint group (1.09 ± 0.14 $M_\odot$), which is qualitatively consistent with the observed distribution dips in M28, and suggests that mass segregation may be responsible for the creation of these distribution dips.

4. We demonstrated that the dynamical age of M28 is comparable to that of Terzan 5 and much smaller than that of 47 Tuc, but it is evolving faster (i.e., with shorter two-body relaxation timescale) than 47 Tuc. Since M28 is located closer to the Galactic center than 47 Tuc, these features may suggest an acceleration effect of cluster dynamical evolution by tidal shock in M28.

5. We show that there is an abnormal deficiency of X-ray sources in the central region ($R \leq 1.5$) of M28 compared with its outskirts, which could be a relic of primordial binary disruption in the central region of GCs. Such a peculiar distribution profile will be erased by the mass segregation effect as clusters evolve to an older dynamical age.

We thank the anonymous referee for the valuable comments that helped to improve our manuscript. This work was supported by China Postdoctoral Science Foundation funded project (2019TQ0288), the National Key Research and Development Program of China No. 2016YFA0400803, the National Natural Science Foundation of China under grants 11622326, 11773015, 11873029, and Project U1838103, U1838201 Supported by NSFC and CAS.

**ORCID iDs**

Zhongqun Cheng @ https://orcid.org/0000-0002-9983-8609
Zhiyuan Li @ https://orcid.org/0000-0003-0355-6437
