The evolution of the Galactic nuclear bulge traced by Cepheid variable stars

Noriyuki Matsunaga
Kiso Observatory, Institute of Astronomy, University of Tokyo, Japan
E-mail: matsunaga@ioa.s.u-tokyo.ac.jp

Abstract. The Galactic nuclear bulge hosts significant populations of young stars, within a few hundred parsecs around the Galactic Centre, unlike the more extended bulge. Recently, we discovered classical Cepheid variable stars (hereinafter Cepheids) in the Galactic nuclear bulge. Their ages are estimated to be $\sim 25$ Myr based on the period-age relation of Cepheids. They are the first clear evidence of star formation a few tens of Myr ago. In addition, the period distribution of the Cepheids indicates that star formation rate was enhanced around $\sim 25$ Myr ago compared to between 30 and 70 Myr ago. Such detailed star formation history has never been obtained for central parts of other galaxies. The timescale of the change in star formation seems to be consistent with the value, $\sim 20$ Myr, suggested for gas inflow into the nuclear bulge. We discuss its implication on the evolution of the nuclear bulge.

1. Introduction

The Galactic Centre region is one of the most interesting places in the Galaxy, with the supermassive blackhole, dense star clusters, massive molecular clouds and so on. It is known that there exist stellar populations with different sizes and different characteristics: the Galactic bulge, the nuclear stellar disk and the nuclear star cluster around the super-massive blackhole [1]. The latter two systems together called the nuclear bulge, within a radius of a few hundred parsecs of the central blackhole, contain young stars of a few Myr old [2], unlike the extended bulge which is dominated by old stars ($\geq 10$ Gyr, [3]). Conspicuous groups of such young stars are massive stellar clusters: the nuclear star cluster, Arches and Quintuplet [4, 5]. All of these clusters are as young as a few Myr, whereas the star formation history remains unclear for times more than $\sim 10^7$ yr ago.

Figer et al. [6] found that a scenario of continuous star formation fits the luminosity function of selected regions towards the nuclear bulge better than scenarios with intensive burst(s) of star formation in the past. On the other hand, Yusef-Zadeh et al. [7] estimated star formation rates in the last $10^5$–$7$ yr based on Spitzer photometry of young stellar objects and other methods, and suggested a temporal change in star formation. Although recent works agree that the recent star formation rate of the nuclear bulge has been roughly $0.1 \, M_{\odot}/\text{yr}$, further observational efforts are necessary to unveil the population of young stellar objects [8]. Moreover, the estimate of the star formation rate $\sim 10^7$ yr ago obtained by Yusef-Zadeh et al. is based on nonthermal radio emission from the nuclear bulge region, whose result has a low time resolution. Some authors claimed that red supergiants and bright red giants may be as young as $10^7$ yr [9, 10], but the age estimates for such objects are difficult because of their complicated processes like mass loss [11]. It is necessary to find other population tracers whose ages can be accurately determined.
We here consider Cepheids in order to investigate the star formation a few tens of Myr ago. They are pulsating giants or supergiants and have pulsation periods roughly between 2 and 50 days. It is well known that they follow a period-luminosity relation, and this allows estimating their distances [12]. Another important characteristic of Cepheids is their period-age relation [13], i.e. the younger Cepheids have the longer pulsation periods. We can also estimate their ages from their periods. However, the survey of Cepheids in the Milky Way is far from complete. In Figure 1, positions of currently known Cepheids [14] are indicated by yellow points. Only objects on the near side of the Sun were found, and no Cepheid at distances near the Galactic Centre were known. The main cause for this is the interstellar extinction towards the Galactic plane, which makes optical surveys of Cepheids difficult, and infrared surveys of variable stars are necessary to overcome this difficulty.

**Figure 1.** Positions of previously known Cepheids [14], indicated by yellow points, plotted over an artist’s impression of the Milky Way (R. Hurt: NASA/JPL-Caltech/SSC) seen from the north Galactic pole.
2. Star formation history of the nuclear bulge traced by Cepheids

We have recently conducted a near-infrared survey of variable stars towards the Galactic Centre using the IRSF telescope and the SIRIUS camera [15] located in South African Astronomical Observatory. In addition to hundreds of Miras [16], we have recently discovered three classical Cepheids [17]. The estimated distances, \( \sim 8 \) kpc, agree well with the distance to the Galactic Centre [16, 18]. Also, the Cepheids receive typical foreground extinctions of the objects around the Galactic Centre, \( \sim 2.5 \) mag in the \( K_s \) band (2.14 \( \mu \)m). These support their membership to the nuclear bulge together with their distribution consistent with the disk-like structure of the nuclear bulge. All the Cepheids we discovered have periods \( \sim 20 \) days, which suggests the ages \( \sim 25 \) Myr based on the period-age relation [13]. The uncertainty in the age estimate is 20 percent, which is taken from the standard deviation of the period-age relation (see [13]). Therefore, they are the first tracers of a stellar population, in the nuclear bulge, with a few tens of Myr whose ages are accurately determined.

A further important finding from our survey is the lack of Cepheids with \( P = 5\,\text{–}\,19 \) days in the nuclear bulge. This is an unexpected result considering period distributions of known Cepheids in the Milky Way and other nearby galaxies [19]. The peak of the period distribution of the MW Cepheids is around 5 days, and objects with longer periods are expected to be less. Considering the period-age relation, the lack of the shorter-period Cepheids in our sample suggests that star formation was less active 30–70 Myr ago compared to 20–30 Myr ago as discussed in [17]. The star formation rate can be estimated from the number of Cepheids assuming the lifetime of Cepheids and the initial mass function. We used the lifetimes from [13] and the initial mass function from [20]. We also assumed that our survey effectively covers roughly 15 per cents of the nuclear bulge to estimate the star formation rate for the entire nuclear bulge. The estimated star formation rate was 0.075 \( M_\odot/\text{yr} \) with a factor of three uncertainty for 20–30 Myr ago. This value is similar to those obtained for the recent few Myr [7, 8]. In contrast, the rate was less than 0.02 \( M_\odot/\text{yr} \) (1 \( \sigma \) upper limit) 30–70 Myr ago.

It is worth while to note that there remain a few uncertainty in our estimates. Especially, the effects of metalicity and the initial mass function are important, and we discussed them in the Supplementary Information of [17]. We concluded that the change in the star formation rate is still significant at the 2 \( \sigma \) level. A similar change was suggested in [7], but our result has a higher time resolution. In addition, the star formation may be also less active between 10–20 Myr. Cepheids in this age range are expected to have periods significantly longer than 20 days, but none of such long-period Cepheids have been found. However, the expected number of such Cepheids is small and we cannot reach a firm conclusion. Massive stars identified in the nuclear bulge are a few Myr old, like the Arches and Quintuplet clusters, but no star aged 10–20 Myr has been confirmed. The star formation history 10–20 Myr ago remains uncertain.

3. Discussion

3.1. Evolution of the nuclear bulge

Here we discuss the implication of the star formation variation on the evolution of the nuclear bulge. It is considered that the star formation rate varies with the gas density, which is known as the Schmidt-Kennicutt relationship [21]. Although it is unclear if such a relation holds for the region close to the Galactic Centre, Yusef-Zadeh et al. [7] found that the star formation rate in the nuclear bulge agrees with the rate expected from the relation. Then, the change in the star formation rate occurred during the last \( 10^7 \) yr suggests the change in the gas density. The current mass of the gas within the nuclear bulge is estimated to be \( \sim 10^7 \) \( M_\odot \) [1]. Gas needs to be supplied to the nuclear bulge in order to make the star formation over the Hubble time possible. Therefore, the star formation history revealed by tracers with various ages is important to consider the circulation and the consumption of interstellar gas around the Galactic Centre.

How do the star formation and the gas density change in the Galactic nuclear bulge, and
what can we learn about the evolution of the Galaxy from the observational results? First of all, the star formation rate obtained for the nuclear bulge is much smaller than those which we find for starburst galaxies. For example, recent observations in the sub-millimetre revealed violent starbursts, \( > 100 \, M_\odot/\text{yr} \), at high redshifts [22, 23]. Such starbursts are considered to be driven by mergers [24, 25], and the merger-driven galaxy formation has been important especially in the early Universe. In comparison with those starbursts, the star formation in the Galactic nuclear bulge is (at least currently) smaller by several orders of magnitude. The Galaxy is relatively isolated from other large galaxies. Although dwarf galaxies may have some effects on the structure of the Galaxy [26, 27], their effects are presumably small on phenomena in the central region of the Galaxy. The evolution of the nuclear bulge is driven by a different process from the merger-driven starbursts. It is suggested by several authors that gas is transformed from the inner disk to the nuclear bulge via the bar-like structure [28, 29, 30]. Moreover, Stark et al. [31] proposed that the star formation in the nuclear bulge can be cyclic with a timescale of \( \sim 20 \) Myr. This scenario is consistent with the change in star formation we found for the nuclear bulge.

This process may be related to evolution of pseudobulges, disk-like stellar components slowly evolved in galaxy centres which are otherwise similar to merger-built classical bulges [32]. The Galactic nuclear bulge seems to be a pseudobulge [33] considering its various characteristics, although its classification and detailed evolution remains to be established [34]. Pseudobulges are considered to be made up of disk gas, and bars play important roles to supply the gas into the central regions of galaxies. In a few cases, star formation in pseudobulges seems to be episodic [35, 36]. The scenario for such evolution of pseudobulges agrees with the observed phenomena, which we discussed above, of the Galactic nuclear bulge.

### 3.2. Future prospects

Because of its proximity, we can observe in detail individual stars and interstellar matter in the Galactic nuclear bulge. For example, a recent investigation revealed a gas cloud of three times the mass of Earth which is approaching Sgr \( A^* \) [37]. The Cepheids and other stars with their ages estimated make it possible to trace the star formation history with a high time resolution. Such detailed investigations on the Galactic nuclear bulge provide us with good opportunities to understand the evolution of bulges. In the following, we discuss future prospects of studies on the Cepheids in the nuclear bulge and the related stars.

First, the motion of the Cepheids is important to consider their properties and origins. Spectroscopic and astrometric observations are required to measure their motions within the nuclear bulge. The Arches cluster has been found orbiting around the Galactic Centre at a high velocity [38]. Although the uncertainty in the distance to the Arches makes the interpretation difficult, its motion is consistent with the rotation in the x2 orbit suggested by [39]. A recent simulation demonstrated that the gas transported from the bar to the nuclear bulge may form a ring along the x2 orbit and star formation occur in the ring [30]. It is interesting to see if the nuclear-bulge Cepheids show motions similar to the Arches or not.

Another important clue to the evolution of the bulge may come from chemical abundances of the Cepheids and other stars around. Figure 2 is a schematic diagram to show the distribution of stellar populations around the nuclear bulge. Within the nuclear bulge, \( r_{\text{GC}} < 0.3 \) kpc, a few Myr old massive stars and the \( \sim 25 \) Myr old Cepheids are known, but the result of our Cepheid survey suggests the lack of stars aged 30 to 70 Myr. In contrast, no evidence has been found for recent star formations in the outer bulge region, indicated by the gray box at \( r_{\text{GC}} = 0.3–3 \) kpc [3]. Although the exact age distribution is not known, Mira variables and other late-type bright stars represent stellar populations with a wide age range, 1–10 Gyr and possibly younger, in the entire bulge [9, 10, 16]. Furthermore, their properties vary as a function of \( r_{\text{GC}} \) indicating the age gradient from the outer region to the nuclear bulge [40]. In the disk exist
stellar populations with various ages including Cepheids, although only several Cepheids in the inner disk have been found so far [41].

| Age       | Distance from the Centre (kpc) |
|-----------|-------------------------------|
| 1 Myr     | 10 Myr                        |
| 100 Myr   | 10 Gyr                        |
| 1 Gyr     | 1 Gyr                         |
| Miras in the Bulge | Miras in the Bulge |
| CEPs in the inner disk |
| CEPs in the NB | CEPs in the NB |
| Massive stars in the NB | Massive stars in the NB |
| Void of young stars | Void of young stars |
| Disk      | Extended Bulge                |
| Nuclear Bulge | Disk                         |

**Figure 2.** Distribution of stellar populations around the Galactic Centre. Various populations are illustrated according to their ages and distances from the Galactic Centre, and their typical tracers are indicated. CEP and NB stand for Cepheid and the nuclear bulge, respectively. See text for the detail.

It is important to understand how the various populations in Figure 2 have been formed. Spectroscopic measurement of their chemical features is expected to be useful for this purpose. For instance, how are the abundances of the nuclear-bulge Cepheids similar to those of the inner-disk Cepheids? Some of the inner-disk Cepheids are slightly older than those in the nuclear bulge, and they might have been formed of similar gas if a part of the inner-disk gas were provided to the nuclear bulge through the bar. How about the abundances of younger massive stars in the nuclear bulge? Massive stars born \( \sim 25 \text{ Myr} \) ago together with the nuclear-bulge Cepheids might have enriched the gas within the nuclear bulge which later forms the younger population. These discussions are rather speculative, but it would be valuable to compare the chemical features of these tracers.

Finally, more and more monitoring surveys are to be revealing a large number of Cepheids and other variable stars like RR Lyr stars in or around the bulge. Recently, the OGLE-III project reported classical and type II Cepheids towards the bulge but a few degree offset from the Galactic plane [42]. Their current survey OGLE-IV covers a wider region including the Galactic plane.\(^1\) Furthermore, the VVV survey is carrying out a monitor survey in the near-infrared, hence more effective for obscured sightlines, for a wide region of the bulge and the disk (520 deg\(^2\)) [43]. Those new samples would be helpful to investigate the evolution of the bulge.

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\(^1\) http://ogle.astrouw.edu.pl/
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