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Cepheids and stellar populations in the Galactic bulge

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Abstract. The characteristics of stellar populations in the Galactic bulge contain essential information for understanding the formation and evolution of the bulge and the Galaxy itself. The central region of the bulge hosts complicated aggregates of various populations, although observational data are still deficient due to some difficulties like the strong foreground extinction. We review recent progresses on survey of variable stars such as Cepheids in the bulge, and discuss stellar populations therein. The surface densities of type II Cepheids and Miras suggest that the nuclear bulge, the central 200 pc region of the bulge, contain these old stars (∼ 10 Gyr).

Key words. Cepheids – Galaxy: bulge

1. Introduction

The Galactic bulge is of great interest in its own right as well as for our understanding of the formation and evolution of the Galaxy and other galaxies. Recent investigations revealed that there are two types of bulges with different formation processes: classical bulges and pseudo-bulges (Kormendy & Kennicutt 2004). While the formers were built in mergers, the latters evolved slowly as disk-like components in galaxy centres. Although some observational features indicate that the Galaxy hosts pseudo-bulge (Binney 2008), the origin and nature of the Galactic bulge remains uncertain yet (Clarkson & Rich 2009).

The Galactic bulge is made up of various stellar populations with different characteristics and extents: the extended bulge, the nuclear bulge and the nuclear stellar cluster around the central black hole (Launhardt et al. 2002). The nuclear bulge has a disk-like stellar distribution with a radius of ∼ 200 pc. In contrast to the more extended bulge (3 kpc in radius) dominated by old stars (≥ 10 Gyr; Zoccali et al. 2003), the nuclear bulge contains young stars of a few Myr old and a large amount of interstellar medium (Serabyn & Morris 1996; Figer et al. 2004). The characteristics (ages and chemical abundances) of the bulge stellar populations are the key to understand its formation and evolution (Ness et al. 2013, and references therein).

In this contribution, we discuss distribution of stellar populations in the Galactic bulge using Cepheids and other variable stars as population tracers. Most of the Cepheid variable stars are separated into two distinct groups: classical Cepheids and type II Cepheids. The former are young intermediate-mass stars (4–10 $M_{\odot}$, 10–300 Myr), while the latters are low-mass stars (∼ 1 $M_{\odot}$, ∼ 10 Gyr; Wallerstein 2002, Sandage 2006). It was found in

1960s that these two groups follow significantly different period-luminosity relations (Fernie 1969). A discussion on the period-luminosity relations of Cepheids and the application to the Galactic Centre distance are given in Matsunaga et al. (2013).

Because different types of Cepheids are found in their particular evolutionary stages of different progenitors, they are not only distance indicators but also good age indicators. Especially, ages of classical Cepheids can be determined accurately thanks to the period-age relation (Bono et al. 2005). Type II Cepheids would indicate the existence of old stellar population (∼ 10 Gyr), although there is no up-to-date set of evolutionary tracks of type II Cepheids after Gingold's work more than two decades ago (Gingold, 1976, 1985).

2. Samples: Cepheids in the bulge

Recent intensive time-series photometric projects discovered a large number of Cepheids and other variables in the Magellanic Clouds. In particular, the third epoch of the Optical Gravitational Lensing Experiment (OGLE) constructed almost complete catalogues of Cepheids in the LMC and SMC (see Table 1). For the Galactic bulge, only a small number of Cepheids had been found until recently (Kubiak & Udalski 2003), but the OGLE-III discovered more than 300 type II Cepheids towards low-extinction regions off the Galactic plane (Soszyński et al. 2011). Most of the photometric projects including the OGLE have been done in the optical wavelength regime, but infrared photometric surveys are necessary to observe obscured objects in the central region of the Galactic bulge. Thus we conducted near-infrared survey of variable stars towards the Galactic Centre using the IRSF telescope in South Africa, and discovered 3 classical Cepheids (Matsunaga et al. 2011) and several type II Cepheids (Matsunaga et al. 2013).

Table 1 lists the numbers of classical and type II Cepheids found in the Magellanic Clouds and the bulge as well as type II Cepheids in globular clusters. As mentioned above, large numbers of classical Cepheids are found in the Magellanic Clouds thanks to the OGLE. In contrast, the numbers of Magellanic type II Cepheids are significantly small. Considering the depth of the OGLE-III survey, these small numbers reflect the short lifetimes and/or the rareness of their progenitors rather than the observational incompleteness. On the other hand, survey of variable stars in the Galactic bulge is far from complete. Nevertheless, the bulge Cepheids found in the recent surveys provide us with important information on stellar populations therein.

Most of the Cepheids we discovered towards the Galactic Centre region have distances consistent with that of the Galactic bulge (8 kpc; Matsunaga et al. 2013). Thus they are considered to belong to the Galactic bulge. Type II Cepheids are as old as RR Lyr variables found in the Galactic bulge. On the other hand, classical Cepheids are significantly young (∼ 25 Myr) and they are the first objects with accurate ages of a few tens of Myr found in the bulge (Matsunaga et al. 2011). Although the uncertainties in distances are slightly larger than the size of the nuclear bulge, we concluded that they belong to the nuclear bulge considering their youth. In this regard, classical Cepheids found by Soszyński et al. (2011) are of particular interest. They are not towards the nuclear bulge. Furthermore, their distances are larger from that of the bulge and do not show a concentration in contrast to the type II Cepheids which are concentrated at the bulge distance (see fig. 7 in Soszyński et al. 2011). Most of the above results agree with previous investigations that young populations are concentrated within the nuclear bulge while only old populations are found in the outer bulge, although origins of the OGLE-III classical Cepheids remain to be investigated.

3. Discussion: surface density profile

We consider the surface density profile of type II Cepheids in order to further discuss the distributions of stellar populations in the bulge. Because our IRSF survey was not so deep as to detect shorter-period type II Cepheids in the bulge, we consider 11 T2Cs with $P > 15$ d. This leads to the density of 66 deg^{-2} con-

Table 1. Numbers of classical and type II Cepheids found in the Milky Way and the Magellanic Clouds. The numbers are taken from the catalogues listed, or compilations for the case of type II Cepheids in globular clusters.

Cepheid type	System	Number	Reference
Classical	LMC	3361	OGLE-III (Soszyński et al. 2008a)
″	SMC	4630	OGLE-III (Soszyński et al. 2010a)
″	Galactic bulge	3†	IRSF (Matsunaga et al. 2011)
″	″	32‡	OGLE-III (Soszyński et al. 2011)
Type II	LMC	179	OGLE-III (Soszyński et al. 2008b)
″	SMC	43	OGLE-III (Soszyński et al. 2010b)
″	Galactic bulge	16†	IRSF (Matsunaga et al. 2013)
″	″	335‡	OGLE-III (Soszyński et al. 2011)
″	Globular clusters	∼ 100	Compilations (Pritzl et al. 2003, Matsunaga et al. 2006)

† The IRSF survey points towards the Galactic Centre region where young stars in the nuclear bulge co-exist with a large number of old stars in the extended bulge. ‡ The OGLE-III survey towards the Galactic bulge covers 68.7 $\deg^2$ of less obscured regions off the Galactic plane.

sidering the area of our survey (1/6 $\deg^{-2}$). However, our survey was not complete even for the relatively long-period T2Cs because of thick dark nebulae, and the above density is an underestimate thus indicated by the arrow in Fig. 1 (a). For the outer bulge region, we calculated the surface density of T2Cs for each OGLE-III region; the surface densities of the OGLE-III T2Cs with $P > 15$ d are indicated by filled circles and all T2Cs by crosses plotted against the angular distance from the Galactic Centre. We considered the OGLE-III fields with $|l| < 2°$, and the profile in Fig. 1 shows the variation along the minor axis in effect. The panel (b) shows a similar plot of the density profile for Miras. Matsunaga et al. (2009) found 547 Miras in the same IRSF survey field, among which 251 objects have periods less than 350 d. Whilst Miras have a broad range of age (from ∼ 10 Gyr to 1 Gyr or even younger), such short-period Miras are considered to belong to the old stellar population like globular clusters (Frogel & Whitelock 1998). The number of the short-period Miras towards the IRSF survey field corresponds to a surface density of 2200 $\deg^{-2}$. The surface densities for the outer region were obtained using the catalogue of the OGLE-II Miras compiled by Matsunaga et al. (2005). The density profile for the OGLE-II Miras is well represented by the exponential law, $N \sim \exp(-0.24r)$, as indicated by filled line in Fig 1 (b). This exponential fits the OGLE-II points better than a de Voucouleurs law (dotted curve) or a Sersic law, $\log N \sim R^{1/n}$, with $n = 2$ (dashed curve). Note that the exponential and the de Voucouleurs law correspond to the Sersic law with $n = 1$ and $n = 4$ respectively. In contrast, the lower limit inferred by the IRSF sample is higher than the exponential law predicted by the OGLE-II Miras. This excess suggests that an additional population of Miras in the nuclear bulge exists. Although the density profile for T2Cs is uncertain due to the small number, it also supports that in the nuclear bulge exists an additional group of T2Cs. Full 2D distribution of these variable stars should show (or reject) the excess more clearly, but this requires intensive photometric survey in the future like the VISTA survey of variable stars in the Milky Way (VVV, Minniti et al. 2010). Furthermore, the physical connection of these old variable stars with the nuclear bulge needs to be confirmed by kinematics, for example. Existence of such old stars would indicate that the formation of the nuclear bulge happened at a rather early phase of the Galactic evolution.

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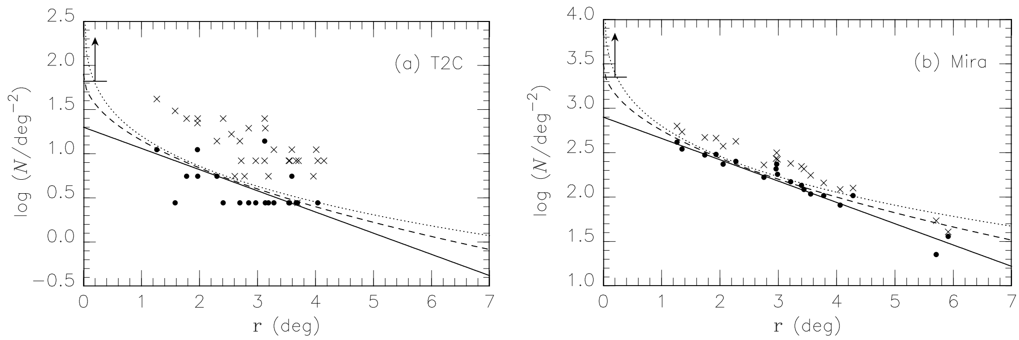

Fig. 1. Density profiles of T2Cs and Miras in the bulge. In the panel (a), crosses and filled circles indicate the surface densities [deg^{-2}] of all T2Cs and those with $P > 15$ d in the OGLE-III fields with $|l| < 2°$ and $|b| < 4°$ (Soszyński et al. 2011). The lower limit of the density of T2Cs with $P > 15$ d in the IRSF survey field towards the Galactic Centre is indicated an the arrow (Matsunaga et al. 2013). In the panel (b), crosses and filled circles indicate the surface densities [deg^{-2}] of all Miras with known periods and those with $P < 350$ d in the OGLE-II fields with $|l| < 2°$ (Matsunaga et al. 2009). An arrow shows the lower limit of the density of Miras with $P < 350$ d towards the IRSF field. The exponential law indicated by the straight lines gives reasonable fits to the OGLE points in the both panels.

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