Age dating the Galactic bar with the nuclear stellar disc

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ABSTRACT
From the decades of the theoretical studies, it is well known that the formation of the bar triggers the gas funnelling into the central sub-kpc region and leads to the formation of a kinematically cold nuclear stellar disc (NSD). We demonstrate that this mechanism can be used to identify the formation epoch of the Galactic bar, using an \textit{N}-body/hydrodynamics simulation of an isolated Milky Way–like galaxy. As shown in many previous literature, our simulation shows that the bar formation triggers an intense star formation for \(\sim 1\) Gyr in the central region and forms an NSD. As a result, the oldest age limit of the NSD is relatively sharp, and the oldest population becomes similar to the age of the bar. Therefore, the age distribution of the NSD tells us the formation epoch of the bar. We discuss that a major challenge in measuring the age distribution of the NSD in the Milky Way is contamination from other non-negligible stellar components in the central region, such as a classical bulge component. We demonstrate that because the NSD is kinematically colder than the other stellar populations in the Galactic central region, the NSD population can be kinematically distinguished from the other stellar populations, if the 3D velocity of tracer stars is accurately measured. Hence, in addition to the line-of-sight velocities from spectroscopic surveys, the accurate measurements of the transverse velocities of stars are necessary, and hence the near-infrared space astrometry mission, \textit{JASMINE}, would play a crucial role to identify the formation epoch of the Galactic bar. We also discuss that the accuracy of stellar age estimation is also crucial to measure the oldest limit of the NSD stellar population.

Key words: methods: numerical – astrometry – Galaxy: bulge – Galaxy: centre – Galaxy: kinematics and dynamics.

1 INTRODUCTION
Revealing the formation history and structure of the bar in the Milky Way is a long-standing challenge in Galactic astronomy. Early infrared observations revealed that the Galactic bulge shows the boxy shape and is believed to be a bar (e.g. Blitz \& Spergel 1991; Nakada et al. 1991). This is supported by the non-circular features in the Galactic longitude and line-of-sight (LOS) velocity of the gas in the central region (e.g. Kerr 1967; Peters 1975; Mulder \& Lien 1986; Athanassoula 1989a,b; Binney et al. 1991). Photometric and spectroscopic surveys towards the Galactic bulge, such as the Bulge Radial Velocity Assay (Kunder et al. 2012), the Abundances and Radial velocity Galactic Origins Survey (Freeman et al. 2013), and VISTA Variables in the Via Lactea (VVV; Minniti et al. 2010), are revealing more detailed structure of the Galactic bar/bulge. Structure analysis using red clump stars from the VVV shows a clear inner boxy/peanut-shaped bulge connected to the long thinner Galactic bar as long as about 5 kpc (Wegg \& Gerhard 2013; Wegg, Gerhard \& Portail 2015). Furthermore, photometric data from Pan-STARRS1 (Chambers et al. 2016), 2MASS (Skrutskie et al. 2006), and AllWISE (Wright et al. 2010), combined with \textit{Gaia} DR2 (Gaia Collaboration et al. 2018) reveal the Galactic bar shape in the inner Galactic disc (Anders et al. 2019). These observations suggest that the orientation of the major axis of the Galactic bar relative to the axis along the Sun and the Galactic centre is about 25\degree (for reviews, Bland-Hawthorn \& Gerhard 2016; Zoccali \& Valenti 2016). Using kinematic data of the bar/bulge stars, recent studies suggest that the current pattern speed of the Galactic bar is about 40 km s\(^{-1}\) kpc\(^{-1}\) (Portail et al. 2017; Bovy et al. 2019; Sanders, Smith \& Evans 2019), as opposed to a fast pattern speed inferred from the kinematics of the solar neighbourhood stars (Dehnen 1999).

Another unknown property of the Galactic bar is the formation time. The Galactic bar impacts the dynamics and star formation of the Galactic disc significantly, and identifying the formation epoch of the bar is one of the key questions to understand the formation and evolution history of the Milky Way. Haywood et al. (2018) discussed that the bar formation at the early epoch quenched star
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2 MODELS AND METHODS

To investigate the effect of bar formation in the Milky Way galaxy, we performed an N-body/hydrodynamics simulation of an isolated galactic bar. We generated the initial axisymmetric model of a Milky Way–like galaxy composed of live stellar/gaseous discs, a live classical bulge, and a fixed dark matter halo. The stellar disc is a scale length (\( R_h \)) and radial extent is \( \sim 50 \) pc. Utilizing APOGEE near-infrared (NIR) spectroscopy data, Nogueras-Lara et al. (2019) argued that the age of the Galactic bar can be deduced. In fact, the VLT/MUSE TIMER Project (Gadotti et al. 2019) relies on this expectation and observes the star formation histories in the inner disc region of external barred galaxies to identify their bar formation epoch (Gadotti et al. 2015).

In this paper, we perform an N-body/hydrodynamic simulation of an isolated Milky Way–like galaxy and test this prediction that the age of the NSD tells us the formation time of the bar. In Section 2, we describe our galaxy model and simulation method. Section 3 describes the formation and evolution of the NSD driven by the bar formation in the simulation. We analyse the age distributions of the stars in the nuclear region of the simulation in Section 4 and discuss an observational challenge to analyse the age distribution of the NSD due to the contamination from the underlying hot stellar components, such as a classical bulge. Finally, we present our conclusions in Section 5.

1Note that the origin of thick and thin disc formation is still highly debated and there are various mechanisms suggested (see e.g. Kawata & Chiappini 2016, for a review). This is merely to provide an example related to the bar formation. In general, the varying star formation rates can explain the transition from the \( \alpha \)-high thick disc to the \( \alpha \)-low thin disc (e.g. Chiappini, Matteucci & Gratton 1997; Brook et al. 2004; Colavitti, Matteucci & Mar Monte 2008).

2Tidal interactions do not necessarily induce bar formation but can destroy a pre-existing bar (e.g. Pfenniger 1991; Berentzen et al. 2003) or impede/cease bar formation (e.g. Moetazedian et al. 2017; Sormani et al. 2018b). Furthermore, N-body/hydrodynamic simulations of isolated barred discs showed that gas that fell into the galactic centre settled into a rotating star-forming nuclear disc (e.g. Friedli & Benz 1995; Athanassoula 2005; Wozniak 2007; Wozniak & Michel-Dansac 2009; Martel, Kawata & Ellison 2013; Carles et al. 2016; Seo et al. 2019). Using N-body/hydrodynamic simulations, Cole et al. (2014) showed that the nuclear stellar disc (NSD) formed in a barred galaxy is a thinner, younger, kinematically ‘cooler’, and more metal rich than the surrounding stars in the bar and bulge (Ness et al. 2014; Debattista et al. 2015, 2018).

The NSD of the Milky Way has been indirectly inferred by modelling the infrared photometric observations with estimated density profiles (Catchpole, Whitelock & Glass 1990; Launhardt, Zylka & Mezger 2002), coinciding with the CMZ. Its vertical extent is \(|b| < 0.4^\circ\) (or \(\sim 50\) pc) and radial extent is \(\sim 150-200\) pc. Utilizing APOGEE near-infrared (NIR) spectroscopy data, Schönrich, Aumer & Sale (2015) detected the rotation of the NSD. Matsunaga et al. (2015) claimed that the LOS velocities of four Cepheids are consistent with the rotation of the NSD. The NSD hosts many young massive stars (Yusef-Zadeh et al. 2009), and there are classical Cepheids in this region (Matsunaga et al. 2011, 2016; Dékány et al. 2015), i.e. there is ongoing star formation (Serabyn & Morris 1996; van Loon et al. 2003; Figer et al. 2004). Recently using accurate photometric data, Nogueras-Lara et al. (2019) argued that the bulk of the NSD stars formed at least 8 Gyr ago and subsequent star formation activity was on a low level until about 1 Gyr ago.

Based on the theoretical studies summarized above, the NSD is considered to be the structure formed after the gas fell into the central disc region due to the bar formation. Because it occupies relatively stable orbits in the bar, the NSD is expected to be difficult to be disrupted unless the bar is broken somehow. Hence, the age of the oldest stars in the NSD should correspond to the age of the stars that formed concurrently with the bar, from which the age of the Galactic bar can be deduced. In the VLT/MUSE TIMER Project (Gadotti et al. 2019) relies on this expectation and observes the star formation histories in the inner disc region of external barred galaxies to identify their bar formation epoch (Gadotti et al. 2015).

In this paper, we perform an N-body/hydrodynamic simulation of an isolated Milky Way–like galaxy and test this prediction that the age of the NSD tells us the formation time of the bar. In Section 2, we describe our galaxy model and simulation method. Section 3 describes the formation and evolution of the NSD driven by the bar formation in the simulation. We analyse the age distributions of the stars in the nuclear region of the simulation in Section 4 and discuss an observational challenge to analyse the age distribution of the NSD due to the contamination from the underlying hot stellar components, such as a classical bulge. Finally, we present our conclusions in Section 5.
The initial condition (i.e. the system is relaxed; see Section 2) of the galaxy model. Left: circular velocity and contributions of individual components as a function of the galactocentric radius, $R$. Center: velocity dispersion of the disc stars (black curves) and radial velocity dispersion of classical bulge stars (thick solid, blue curve) as a function of $R$. Right: Toomre’s $Q$ values of the disc stars ($Q_{\text{disc}}$) and the disc stars + gas ($Q_{\text{tot}}$) as a function of $R$.

Note that we took into account the continuous gas accretion to the disc from the halo by adding new gas smoothed particle hydrodynamic (SPH) particle at $|z| = 5$ kpc. The gas particles were continuously added at the rate of $2 \times 10^3$ M$_\odot$ yr$^{-1}$, which is comparable to the total star formation rates (SFR) of the simulated galaxy. The gas particles were added following the exponential radial profile with the scale length, $R_d$, within the radius of 20 kpc. The initial velocity of the added SPH particles was set to be azimuthal motion of the local circular velocity with an isotropic velocity dispersion, whose mass and scale length are $6.7 \times 10^9$ M$_\odot$ and 0.79 pc, respectively. For simplicity, we assume the dark matter halo to be a static potential, whose density profile follows the Navarro--Frenk--White profile. We assigned the mass and concentration parameter at 1.26 and 11.2, respectively. A more detailed model description can be found in Baba (2015).

Our simulations were performed using the N-body/SPH simulation code ASURA-2. To perform time integration, we used leapfrog integrator with variable and individual time-steps. ASURA-2 also implements a time-step limiter (Saitoh & Makino 2009) that allows us to solve rapid expansions of the gas shell due to supernovae by imposing sufficiently small time-steps to neighbouring particles. The FAST method (Saitoh & Makino 2010), which speeds up the time integration of a self-gravitating fluid by using different time-steps for gravity and the hydrodynamic interactions of each particle, was also implemented. We computed self-gravity with the Tree/GRAPE method (Makino 1991) using a software emulator of GRAPE known as Phantom-GRAPE (Tanikawa et al. 2013). The simulations also take into account radiative cooling for a wide temperature range of $20 \, \text{K} < T < 10^6 \, \text{K}$, heating due to far-ultraviolet background radiation, probabilistic star formation from the cold dense gas, and thermal feedback from Type II supernovae (Saitoh et al. 2008) and H$_\text{II}$ regions (Baba, Morokuma-Matsui & Saitoh 2017). This is the same model as is used in Baba et al. (2017), where more details of the simulations are described. Dynamics of spiral arms in the simulated barred galaxy using the same model have been presented in Baba (2015). The dynamical evolution of the bar and bulge and link to the NSD are analysed in this paper.

The initial numbers of stars and gas (SPH) particles are 5.7 million and 4.5 million, respectively, with particle masses for star particles and gas particles at approximately $9.1 \times 10^5$ M$_\odot$ and $3 \times 10^5$ M$_\odot$, respectively. We used a gravitational softening length of 10 pc, which is sufficiently small to resolve the three-dimensional structure of a disc galaxy (Baba, Saitoh & Wada 2013). As described above, a disc galaxy model in a near-equilibrium state was generated using Hernquist’s method (Hernquist 1993). Next, to allow the system to dynamically relax, it was evolved for 6 Gyr with the SPH particles fixed and the star particles randomly displaced azimuthally at every several time-steps to prevent the growth of non-axisymmetric features (McMillan & Dehnen 2007). Next, the circular velocity of the SPH particles was reassigned based on the mass distribution after the system was relaxed. This equilibrium state was used as the ‘initial condition’ for the numerical simulation.

Figure 1 shows the initial circular velocity, velocity dispersion of the classical bulge and disc stars, and initial Toomre’s $Q$ value of the disc stars ($Q_{\text{disc}}$) as a function of the galactocentric radius, $R$. We note that gravitational interactions between the stellar and the gaseous components make a galaxy more unstable than the two components considered individually (Jog & Solomon 1984).

In the mixed component model, an effective Toomre’s $Q$ value is approximately given by $Q_{\text{tot}}^{-1} \approx Q_{\text{star}}^{-1} + Q_{\text{gas}}^{-1}$, where $Q_{\text{gas}}$ is the $Q$ value of the gas (Wang & Silk 1994). The radial profile of the initial $Q_{\text{tot}}$ value is also shown in Fig. 1. There is no vertical cut applied to select the particles. The $Q$ values are computed based on the radial velocity dispersion.

### 3 BAR-DRIVEN GROWTH OF NUCLEAR DISC

We run the simulations for about 5 Gyr and display time evolution of face-on stellar distributions in the top row of Fig. 2. In this particular model, grand-design spiral arms form in the discs at $t \lesssim 1$ Gyr. A stellar bar starts developing around $t = 1.0$ Gyr, and a bar with a semi-major axis of $\sim 3$ kpc is fully developed at $t = 1.5$ Gyr. These time-scales of the spiral and bar formation are due to the initially unstable initial condition. To investigate time evolution of the stellar bar, we measure the bar strength and pattern speed with the $m = 2$ mode.
Fourier amplitude of the stellar surface mass density, $A_2$, given by

$$A_2 = \frac{\sum_{j=1}^{N} m_j e^{2i\phi_j}}{\sum_{j=1}^{N} m_j}.$$  \hspace{1cm} (1)

Here $m_j$, $\phi_j$, and $N$ are the mass and azimuth angle of a $j$th stellar particle, and the number of stellar particles within a cut-off radius of $R_\ast = 3.5$ kpc, respectively (e.g. Dubinski, Berentzen & Shlosman 2009). Fig. 3(a) shows the evolution of the bar amplitude ($|A_2|$). The bar starts to grow in a time of $t \gtrsim 1$ Gyr and then reaches the maximum amplitude around $t \simeq 1.8$ Gyr. After that, the bar slowly decreases its amplitude.

The middle and bottom panels of Fig. 2, respectively, show the $x$–$y$ and $x$–$z$ maps of the stars (coloured by orange) and gas (dark) distribution in the central region (enclosed by squares in the top panels). We can see the stellar and gas discs in the central sub-kpc region in the snapshots after the bar formation starting at $t = 1$ Gyr. Hereafter, we refer these stellar and gas disc structures as NSD and NGD, respectively. The radius and thickness of the NSD are $\sim 800$ pc and $<100$ pc, respectively. The radius and thickness of the NGD are $\sim 800$ pc and $\lesssim 10$ pc, respectively (See also Appendix A1). These sizes are much larger than the observed NSD in the Milky Way. For example, the radial extent of the NSD in the Milky Way is around 230 pc (Launhardt et al. 2002), and the vertical scale height is measured to be around 45 pc (Nishiyama et al. 2013). Note that the aim of this study is to explore the phenomenological link between the Galactic bar structure and the NSD, not to reproduce the NSD and NGD structures in the Milky Way with the numerical simulation. Therefore, the discrepancy in the size of the nuclear discs between our simulation and the Milky Way is not an issue in this study. We consider that the discussion in this paper does not depend on the size of the nuclear disc.

Fig. 3(b) shows the time evolution of masses of the gas and stars in the central 1 kpc region. We consider that the gas and the newly born stars after $t = 0$ Gyr reside mainly in the nuclear disc in our simulation. Hence, we refer to the gas and the newly born stellar mass within 1 kpc as NSD and NGD in this panel. After bar formation starts at $t \gtrsim 1$ Gyr, the NSD mass ($M_{\text{NSD}}$) rapidly increases until the bar is fully formed at $t \approx 1.5$ Gyr. At this point, the increase of the NSD mass slows down, reaching $10^9 M_\odot$ at $t = 3$ Gyr. This mass is similar to the NSD mass of the Milky Way, around $1.4 \times 10^8 M_\odot$ (Launhardt et al. 2002). In contrast, the NGD mass ($M_{\text{NGD}}$) increased as the bar grew at $t = 1 - 1.5$ Gyr due to the inflow of gas triggered by bar formation (see also Appendix A2). However, the NGD mass reached a quasi-steady value of about $10^8 M_\odot$ after the bar fully formed. This mass is also similar to the observed value for the NGD of the Milky Way, around $5 \times 10^7 M_\odot$ (Launhardt et al. 2002), although the size of the disc is much larger. Note that the bar formation triggers inflow of not only gas but also older stars into the central region. In fact, $M_{\text{CB}}$ in Fig. 3(b) represents the evolution of the mass of the old stars, i.e. classical bulge and old disc stars, already in place at $t = 0$ Gyr in our simulation; it increases by a factor of about 1.2 after the bar formation.

The decrease of $M_{\text{NGD}}$ after $t \approx 1.3$ Gyr is mainly due to the consumption of gas during star formation. As shown in Fig. 3(c), in situ SFR in the central 1 kpc region rapidly increased at $t = 1.2$ Gyr, reaching a maximum value in the growth phase of the bar ($t \sim 1.0 - 1.5$ Gyr). Then, the SFR decreases to a value of about $0.25 M_\odot$ yr$^{-1}$ with some intermittent spikes. This quasi-steady value is roughly consistent with the values obtained by the previous simulations (e.g. Kim et al. 2011; Shin et al. 2017) and the observations of the Milky Way of $\sim 0.01 - 0.1 M_\odot$ yr$^{-1}$ (e.g. Yusef-Zadeh et al. 2009).
Interestingly, starburst occurs during the bar-growing phase (1 Gyr < t < 2 Gyr). Previous hydrodynamics simulations of barred galaxies have shown that gas inflow along the bar usually induces the increased star formation in the central sub-kpc regions (e.g. Heller & Shlosman 1994; Friedli & Benz 1995; Seo et al. 2019) with an associated reduction of star formation in the bar (Fanali et al. 2015; Donohoe-Keyes et al. 2019) (See Appendix A2 for the evolution of the gas density profile due to the bar formation). This result suggests that revealing the star formation history of the NSD in the Milky Way galaxy can be used to help identify the formation epoch of the Galactic bar, because the NSD consists of the stars formed after the bar formation and the age distribution of the NSD should be peaked at the age of the bar formation. The definition of the bar formation epoch is not clear; as shown in these results, it spreads over from t = 1.0 to t = 1.8 Gyr in this simulation. Just for a convenience of the discussion below, in this paper we consider t = 1.5 Gyr as the formation time of the bar in this simulation, because morphologically the bar is fully developed (Fig. 2), and it is about a middle of the bar formation period. However, this is merely a rough time of reference for the formation time of the bar. It rather means that the bar formation period is around this time and spreads over about 1 Gyr.

4 AGE DISTRIBUTION OF NUCLEAR DISC STARS

As shown in the previous section, gas inflow due to bar formation causes the subsequent intense star formation. Hence, it can be estimated when the bar is formed from the age distribution of the NSD. In practice, it is challenging to estimate the age of a star precisely; however, there are various methods to infer the stellar age for different stellar populations (see Soderblom 2010; for a review). In this theoretical work, first we consider an ideal case that the age of the tracer stellar population is accurately measured in some way, and the effects of the observational uncertainties are briefly discussed later in Section 5. A remaining challenge is to measure the age distribution of the NSD accurately, when there is contamination from the other stellar components in the Galactic centre region.

One of still unknown stellar component, which could be a non-negligible ‘hot’ stellar component in the central region of the Milky Way galaxy, is a ‘classical bulge’, which may be formed in the early stages of galaxy formation (Kormendy & Kennicutt 2004), and hidden in the current observational constraints (Shen et al. 2010; Kunder et al. 2016). In fact, as shown in Section 2, our simulation includes a classical bulge component. In this section, we discuss how the age distribution of the NSD can be recovered if there is a non-negligible classical bulge component in the central region of the Milky Way. The exercise below does not intend to evaluate feasibility of identifying the age distribution of the NSD in any particular observational data but to demonstrate what kind of the observational information would be required to minimize the contamination from the other hot stellar component and extract the age distribution of the NSD only.

To this end, we placed an observer at a distance of 8 kpc from the galactic centre in the disc mid-plane of the simulated disc galaxy with an angle of 25° from the major axis of the bar (Bland-Hawthorn & Gerhard 2016). Because we are interested in the relative velocity within the central region, we do not consider the uncertainty of the solar peculiar motion either, that is, the observer is assumed to have a rotational speed of 200 km s⁻¹, and no vertical or radial velocity for simplicity. Again, we consider an ideal case that one star particle is one tracer star in the central region and ignore any observational error.

We first select the star particles within the volume of Galactic longitude |l| < 5°, Galactic latitude |b| < 0.3°, and distance from the observer of 7 < d < 9 kpc⁴ to spatially extract the stars in the NSD of the simulated galaxy. We name this sample of stars the ‘Mock-Spatial’ sample. Left-hand panels of Fig. 4 show the spatial distribution in Galactic coordinate, l–vlos distribution, l–vθ distribution, and l–vφ distribution from top to bottom for the Mock–Spatial sample, where vlos, vθ, and vφ are LOS velocity and transverse velocities in the directions of Galactic latitude and longitude, respectively. In Fig. 4, green dots represent NSD stars, which are defined as newborn stars formed after the simulation started, because the majority of the newborn stars formed in the NSD in the central region (Fig. 3). In contrast, red crosses represent the classical bulge component, which was initially placed in the simulation. The Galactic longitude and latitude selections for the

⁴This distance cut has been made for simplicity. This can be achieved if the uncertainty in the distance measurement is less than 10 per cent, which could become feasible with the future NIR astrometry missions, such as JASMINE and GaiaNIR (see Section 5).
Mock–Spatial sample were made to focus on the region where the NSD is prominent; however, significant contamination from the classical bulge component is evident. In this sample, we found the classical bulge particles with \(8.37 \times 10^8 \, M_\odot\) and the NSD particles with \(8.31 \times 10^8 \, M_\odot\) (Table 1). Note that in the central region, there is also a stellar disc component, which represents both thick and thin discs. However, the age distribution of the thin disc is spread over a wide range, and it is easier to be distinguished from the NSD age distribution, which should suddenly increase when the bar formed. The thick disc could have a peaked age distribution, which

| Mock          | CIB  | NSD  |
|---------------|------|------|
| Mock–Spatial  | 8.4  | 8.3  |
| Mock–LOSV    | 1.6  | 2.8  |
| Mock–TANV    | 0.1  | 1.1  |
could blur the sudden increase of the NSD stars at the formation epoch of the bar, if their formation epoch is closer. However, in our simulation, the age distribution for an old thick disc is similar to what we consider for the classical bulge below. Also, in the central region, velocity dispersion of the thick disc should be quite high and kinematically similar to the classical bulge component. Therefore, in this paper we consider only the contamination from the classical bulge component, which we believe would be most serious in the central region.

The age distribution of the Mock–Spatial sample is shown in top panels of Fig. 5 with a blue dashed line. Here, we assumed that the age distribution of the classical bulge follows a Gaussian distribution with a mean age, which is referred to as the formation time, and a dispersion of 0.25 Gyr, to mimic a starburst of classical bulge. We define $t_{\text{gap}}$ as the time difference between the classical bulge formation time and the bar formation time, which corresponds to $\text{Age}_{\text{bar}} = 3.5$ Gyr (or $t = 1.5$ Gyr in Fig. 3). Top panels of Fig. 5 show the results with different $t_{\text{gap}}$ obtained by adjusting the formation time of the classical bulge but with a fixed age of bar formation. When $t_{\text{gap}}$ is greater than 2 Gyr, the formation of the NSD can be clearly distinguished from the starburst of classical bulge formation. As a result, a clear drop of stars older than $\text{Age}_{\text{bar}} = 3.5$ Gyr can be easily identified. However, when $t_{\text{gap}} = 1$ Gyr (top-left panel in Fig. 5), it is difficult to identify the oldest age of the NSD, as it overlaps with the age distribution of the classical bulge, and the Mock–Spatial sample contains significant classical bulge components. Note that the quantitative discussions provided here do not precisely apply to the Milky Way, because we do not know the mass or age distribution of its classical bulge or NSD. For example, if the distribution of the age of the classical bulge is much broader, larger $t_{\text{gap}}$ would be required to distinguish between the NSD from the classical bulge. However, if the mass or number of the tracer stars of the classical bulge is smaller, it would be easier to identify the NSD formation time. To demonstrate this, the lower panels of Fig. 5 show the results if the contribution from the classical bulge is one-tenth of the assumed value in the upper panel. The contribution of the classical bulge is significantly reduced; however, it is still challenging to distinguish the gap of the age between the classical bulge and the NSD, if the age gap is too small.

We can use velocity information to further constrain the sample selection of the NSD to reduce contamination from the classical bulge (i.e. hot component). LOS velocity in the Galactic centre is already obtained with the current facility (e.g. Matsunaga et al. 2015; Schönrich et al. 2015). We therefore add the selection criterion using the LOS velocity information ($l - v_{\text{los}}$) to Mock–Spatial. The middle panels of Fig. 4 show this sample of ‘Mock–LOSV’, and
the second top panel shows our selection using the LOS velocity. In general, the classical bulge is not rotating, having more isotropic velocities, whereas the NSD is rotation dominant. Therefore, the classical bulge component contamination is reduced by the LOS velocity selection, and the NSD component is relatively increased (see Table 1). The age distribution of the Mock–LOSV sample is shown by the red dot-dashed line in Fig. 5. Although the contamination of the classical bulge component is less than that of the Mock–Spatial sample, it can be seen that it is still not easy to distinguish the NSD age distribution from the age distribution of the classical bulge component for the case of $t_{\text{gap}} = 1$ Gyr. Even if the classical bulge mass is reduced to one-tenth of what used in the simulation (lower panels), it is difficult to distinguish the NSD from the classical bulge component with $t_{\text{gap}} = 1$ Gyr.

Finally, we consider the case where transverse velocity information is available and select the sample using the full 3D velocity information. Since the NSD stars are kinematically colder, $|v_b|$ should be small, which is seen in the third row panels in Fig. 4. The NSD stars also are distributed in a ring-like structure in the $l$–$v_l$ plane, as seen in the bottom panels in Fig. 4, because of the significant rotation of the NSD. Based on these, we further reduce the sample from the Mock–LOSV sample (see Table 1), using $|v_b|$ and $v_l$ as shown in the third and fourth row panels in the right column of Fig. 4, which we refer to as the ‘Mock–TANV’ sample. The age distribution of the Mock–TANV sample is shown by the black solid line in Fig. 5, where it can be seen that contamination by the classical bulge component is significantly reduced. Consequently, the NSD stands out in this sample, and it is possible to identify the formation time of the NSD, i.e. the bar formation time.

These results demonstrate that in order to identify the formation time of the NSD, the challenge to reduce the contamination from the classical bulge must be addressed due to their spatial overlap. Our results highlight that obtaining 3D velocity information of the tracer sample is an effective way to reduce the contamination and extract the NSD component more clearly.

5 DISCUSSION

Using an $N$-body/SPH simulation of a Milky Way–like galactic disc, we demonstrate that the NSD forms from the excessive gas falling into the central region when the bar forms, and hence, a sudden drop in the number of the old stars in the age distribution of the NSD reveals the formation time of the bar. Bar formation triggers the inflow of the gas into the central region, which causes a rapid increase of star formation in the nuclear disc region. Once the NSD forms, which enables to identify the age of NSD clearly and provide the accurate measurement of the transverse velocity of the NSD stars, which enables to identify the age of NSD clearly and hence a definitive formation time of the Galactic bar. JASMINE is planned to be launched in mid-2020s and is designed to achieve $Gaia$-level astrometric accuracy at the Galactic centre in the NIR band ($H_k$-band, 1.1–1.7 $\mu$m). JASMINE will observe the Galactic centre region within about 200 pc from the Galactic centre and will achieve the parallax accuracy of $\sigma_\pi \approx 25$ $\mu$as and the proper motion accuracy of $\sigma_\mu \approx 25$ $\mu$as yr$^{-1}$ for the objects brighter than $H_k = 12.5$ mag and the proper motion accuracy of $\sigma_\mu \approx 125$ $\mu$as yr$^{-1}$ for the objects brighter than $H_k = 15.0$ mag. Hence, JASMINE will achieve about 1.6 kpc and 1 km s$^{-1}$ accuracy in distance and transverse velocities ($v_l$ and $v_h$), respectively, for bright tracer stars in the Galactic centre region, respectively. Fig. 6(a) shows the age distributions of the stars in the central region (as shown in the top-right panel of Fig. 5 with $t_{\text{gap}} = 2$ Gyr) with these uncertainties included. We can see that the distance and velocity uncertainties it is considered that the last major merger occurred about 10 Gyr ago (Belokurov et al. 2018; Helmi et al. 2018), following which the Galactic disc experienced rather quiet evolution (Brook et al. 2004). As such, it is likely that the bar in the Milky Way has not been disrupted since formation. Thus, the NSD is likely to have survived since formation of the bar, which allows us to use the stellar age distribution of the NSD to provide a robust way of measuring the age of the Galactic bar. If strong feedback from the central black hole (e.g. Shlosman et al. 1989) destroyed the NGD and suppressed the star formation of the NSD for some period, the age distribution of the NSD would not be smooth. However, as long as the compact and kinematically cold NSD is not destroyed, the oldest population should stay in the NSD, which still helps us to infer the epoch of the Galactic bar formation.

We do not mean to claim that the age of the NSD is the only one or best way to identify the age of the bar. Ideally, we should have several independent ways to infer the epoch of the bar formation, so that the bar formation epoch would be more confidently measured. More studies of the bar formation and their impact to the stellar population distribution in the Milky Way are encouraged.

A challenge in identifying the stellar population in the NSD is to distinguish it from the underlying ‘hot’ stellar component, such as a classical bulge, whose mass in the central region is still unknown but could be non-negligible. We demonstrated that 3D velocity information is crucial to minimize the contamination of a classical bulge component in order to clearly identify the formation time of the NSD. LOS velocities can be obtained from the NIR multi-object spectrographs, such as APOGEE-2 (Blanton et al. 2017) and MOONS at the ESO/VLT (Cirasuolo & MOONS Consortium 2016). Transverse velocities are required to be measured with astrometry. Unfortunately, the optical astrometry mission, Gaia (Collaboration et al. 2016), cannot see the NSD because of heavy dust extinction in the optical band. Recently, the proper motion was measured from the VVV survey data and the VIRAC catalogue (Smith et al. 2018), with a median uncertainty of 0.67 mas yr$^{-1}$ for stars with $11 < K_s < 14$ mag. The absolute proper motion is also measured using the Gaia reference frame (Clarke et al. 2019; Sanders et al. 2019).

Ultimately, NIR astrometric space missions, such as the Japan Astrometry Satellite Mission for Infrared Exploration (JASMINE; Gouda 2012)$^5$ and the GaiaNIR (Hobbs et al. 2016, 2019), will provide the accurate measurement of the transverse velocity of the NSD stars, which enables to identify the age of NSD clearly and hence a definitive formation time of the Galactic bar.

We note that the model galaxy in this study is an idealized isolated disc model. Thus, the resulting NSD is purely of the internal origin. If the galactic disc experienced a merger, the bar and NSD could be destroyed (de Avillez et al. 2018; Debattista et al. 2019a; Fragkoudi et al. 2019). For the Milky Way, it is likely that the bar in the Milky Way has not been disrupted since formation. Thus, the NSD is likely to have survived since formation of the bar, which allows us to use the stellar age distribution of the NSD to provide a robust way of measuring the age of the Galactic bar. If strong feedback from the central black hole (e.g. Shlosman et al. 1989) destroyed the NSD and suppressed the star formation of the NSD for some period, the age distribution of the NSD would not be smooth. However, as long as the compact and kinematically cold NSD is not destroyed, the oldest population should stay in the NSD, which still helps us to infer the epoch of the Galactic bar formation.

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$^5$http://jasmine.nao.ac.jp/index-en.html
minimally affect the selection of the stars and therefore minimally
affect the age distribution.\footnote{Additional complexity in real
observational data is crowding. However, because JASMINE focuses
on only brighter stars, crowding is less serious.}

However, the accuracy of age estimation is crucial. To assess the
effect of the age uncertainty, we add the age uncertainties of
$\sigma_{\text{age}} = 0.3$, 1, and 3 Gyr in Figs 6(b), (c), and (d), respectively.
If the age uncertainty is as small as 0.3 Gyr, it does not affect the
age distribution analysis significantly (Fig. 6b). Age uncertainty
greater than 1 Gyr (Figs 6 c and d) makes it difficult to identify the
sharp decrease of the NSD stars, because the time-scale of the bar
formation is about 1 Gyr. Then, age uncertainty greater than 1 Gyr
also makes it difficult to identify the gap between the NSD and the
classical bulge stellar population, depending on the uncertainty and
the difference in their ages. This highlights that measuring the age of
stars in the Galactic centre region is crucial to age dating the Galactic
bar through the age of the NSD stars. For example, Mira variables
are bright enough to be observed with JASMINE (Matsunaga et al.
2009) and are also known to follow the age–period relation (Feast,
Whitelock & Menzies 2006; Grady, Belokurov & Evans 2019).
Hence, the accurate calibration for the age measurement of Mira
variables is crucial for JASMINE to identify the formation time of
the NSD; the formation time of the Galactic bar can then be deduced
from their age distribution.

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\textbf{REFERENCES}

Anders F. et al., 2019, A&A, 628, A94
Athanassoula E., 1989a, Plasma Astrophysics, Vol. 1, NASA, United State,
p. 341
Athanassoula E., 1989b, in Sellwood J. A., ed., Dynamics of Astrophysical
Discs, Cambridge University Press, Cambridge, United Kingdom, p. 145

\textbf{MNRAS} \textbf{492}, 4500–4511 (2020)
Ortolani S., Renzini A., Gilmozzi R., Marconi G., Barbuy B., Bica E., Rich R. M., 1995, *Nature*, 377, 701
Ostriker J. P., Peebles P. J. E., 1973, *ApJ*, 186, 467
Peters W. L. I., 1975, *ApJ*, 195, 617
Pfenniger D., 1991, in Sundelius B., ed., *Dynamics of Disc Galaxies*. Göteborgs University and Chalmers University of Technology, Göteborg, Sweden, p. 191
Pfenniger D., Friedli D., 1991, *A&A*, 252, 75
Piner B. G., Stone J. M., Teuben P. J., 1995, *ApJ*, 449, 508
Portail M., Gerhard O., Wegg C., Ness M., 2017, *MNRAS*, 465, 1621
Raha N., Sellwood J. A., James R. A., Kahn F. D., 1991, *Nature*, 352, 411
Regan M. W., Teuben P. 2003, *ApJ*, 582, 723
Regan M. W., Teuben P. J., 2004, *ApJ*, 600, 595
Riddle M. G. L., Sormani M. C., Treß R. G., Magorrian J., Klessen R. S., 2017, *MNRAS*, 469, 2521
Rix H.-W., Zaritsky D., 1995, *ApJ*, 447, 82
Roberts W. W., Jr., Huntley J. M., van Albada G. D., 1979, *ApJ*, 233, 67
Saitoh T. R., Makino J., 2009, *ApJ*, 697, L99
Saitoh T. R., Makino J., 2010, *PASJ*, 62, 301
Saitoh T. R., Daisaka H., Kokubo E., Makino J., Okamoto T., Tomisaka K., Wada K., Yoshihara N., 2008, *PASJ*, 60, 667
Sanders R. H., Huntley J. M., 1976, *ApJ*, 209, 53
Sanders J. L., Smith L., Evans N. W., 2019, *MNRAS*, 488, 4552
Sanders J. L., Smith L., Evans N. W., Lucas P., 2019, *MNRAS*, 487, 5188
Sarzi M., Ledo H. R., Dotti M., 2015, *MNRAS*, 453, 1070
Schönrich R., Aumer M., Sale S. E., 2015, *ApJ*, 812, L21
Seo W.-Y., Kim W.-T., 2013, *ApJ*, 769, 100
Seo W.-Y., Kim W.-T., Kwak S., Hsieh P.-Y., Han C., Hopkins P. F., 2019, *ApJ*, 872, 5
Seredyn E., Morris M., 1996, *Nature*, 382, 602
Shen J., Rich R. M., Kormendy J., Howard C. D., De Propris R., Kunder A., 2018, *ApJ*, 720, L72
Shin J., Kim S. S., Babu J., Saitoh T. R., Hwang J.-S., Chun K., Hozumi S., 2017, *ApJ*, 841, 74
Shlosman I., Frank J., Begelman M. C., 1989, *Nature*, 338, 45
Skrutskie M. F. et al., 2006, *AJ*, 131, 1163
Smith L. C. et al., 2018, *MNRAS*, 474, 1826
Soderblom D. R., 2010, *ARA&A*, 48, 581
Sormani M. C., Sobacchi E., Fragkoudi F., Ridley M., Treß R. G., Glover S. C. O., 2018a, *MNRAS*, 481, 2
Sormani M. C., Treß R. G., Ridley M., Glover S. C. O., Klessen R. S., Binney J., Magorrian J., Robitaille T. R., 2018b, *MNRAS*, 475, 2383
Tanikawa A., Yoshikawa K., Nitadori K., Okamoto T., 2013, *New A.*, 19, 74
van Albada G. D., Roberts W. W., 1981, *ApJ*, 246, 740
van Albada T. S., Sanders R. H., 1982, *MNRAS*, 201, 303
van Loon J. T. et al., 2003, *MNRAS*, 338, 857
Wada K., Habe A., 1992, *MNRAS*, 258, 82
Wang B., Silk J., 1994, *ApJ*, 427, 759
Wegg C., Gerhard O., 2013, *MNRAS*, 435, 1874
Wegg C., Gerhard O., Portail M., 2015, *MNRAS*, 450, 4050
Wozniak H., Michel-Dansac L., 2009, *A&A*, 465, L1
Wozniak H., Michel-Dansac L., 2009, *A&A*, 494, 11
Wright E. L. et al., 2010, *AJ*, 140, 1868
Yusef-Zadeh F. et al., 2009, *ApJ*, 702, 178
Zoccali M., Valenti E., 2016, *PASA*, 33, e025
Zoccali M. et al., 2003, *A&A*, 399, 931
Zoccali M. et al., 2006, *A&A*, 457, L1

**APPENDIX A: BAR-DRIVEN GAS INFLOW**

**A1 Nuclear gas disc size**

The formation mechanism of nuclear disc is still under debate. The widely believed theory is that the inner Lindblad resonance (ILR) is related to the location of nuclear disc (Buta & Combes 1996; Combes 1996). Alternatively, Regan & Teuben (2003), Regan & Thomas (2004) argued that the existence of $x_2$-orbits leads to the formation of nuclear disc. They also reminded that the ILR radius in strong bars is not a true resonance but an approximated radius.

The ILR radius seems to be related to constrain the nuclear disc size (Combes 1996). Alternatively, Regan & Teuben (2003), Regan & Thomas (2004) argued that the existence of $x_2$-orbits leads to the formation of nuclear disc. They also reminded that the ILR radius in strong bars is not a true resonance but an approximated radius.

although the time evolution of the disc sizes follows the similar evolutionary trend to the ILR radius. As Li et al. (2015) suggested, the ILR radius seems to be related to constrain the nuclear disc size but not the same as the size of the nuclear disc.

**Teuben (2004) argued that the existence of $x_2$-orbits leads to the formation of nuclear disc.**

**A2 Bar-driven gas removal in the bar region**

To understand the relationship between the bar growth and gas infall, we analysed the time evolution of the radial profiles of the bar amplitude ($\delta_2$; e.g. Rix & Zaritsky 1995) and gas surface density ($\Sigma_{gas}$) as shown in Fig. A2. Prior to the bar formation ($t = 1$ Gyr), the gas density followed an exponential profile as assumed in the initial condition. After the bar formation ($t > 1.5$ Gyr), the gas density started to decrease at the radius of around 1 kpc. At this point, the...
bar amplitude attained its maximum value and the gas density at the centre simultaneously started to increase. Subsequently, the gas depleted region at \( R \gtrsim 0.5 \) kpc widened outwards and its outer edge reached a radius of around 3.3 kpc at \( t = 4 \) Gyr. The radius of the outer edge of the gas-depleted region was approximately equal to the ultra-harmonic (1:4) resonance radius (i.e. about 3.5 kpc) in our simulated barred galaxy. This depletion of the gas in the bar region leads to the reduction of star formation rate in the bar.

**Figure A2.** Temporal change of radial profiles of (upper) gas surface density and (lower) normalized Fourier amplitude. Shaded area indicates the bar region.