Stellar halos and elliptical galaxy formation: Origin of dynamical properties of the planetary nebular systems

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ABSTRACT

Recent spectroscopic observations of planetary nebulae (PNe) in several elliptical galaxies have revealed structural and kinematical properties of the outer stellar halo regions. In order to elucidate the origin of the properties of these planetary nebula systems (PNSs), we consider the merger scenario in which an elliptical galaxy is formed by merging of spiral galaxies. Using numerical simulations, we particularly investigate radial profiles of projected PNe number densities, rotational velocities, and velocity dispersions of PNSs extending to the outer halo regions of elliptical galaxies formed from major and unequal-mass merging. We find that the radial profiles of the projected number densities can be fitted to the power-law and the mean number density in the outer halos of the ellipticals can be more than an order of magnitude higher than that of the original spiral’s halo. The PNSs are found to show a significant amount of rotation (\(V/\sigma > 0.5\)) in the outer halo regions (\(R > 5R_e\)) of the ellipticals. Two-dimensional velocity fields of PNSs are derived from the simulations and their dependences on model parameters of galaxy merging are discussed in detail. We compare the simulated kinematics of PNSs with that of the PNS observed in NGC 5128 and thereby discuss advantages and disadvantages of the merger model in explaining the observed kinematics of the PNS. We also find that the kinematics of PNSs in elliptical galaxies are quite diverse depending on the orbital configurations of galaxy merging, the mass ratio of merger progenitor spirals, and the viewing angle of the galaxies. This variation translates directly into possible biases by a factor of two in observational mass estimation. However, the biases in the total mass estimates can be even larger. The best case systems viewed edge-on can appear to have masses lower than their true mass by a factor of 5, which suggests that current observational studies on PNe kinematics of elliptical galaxies can significantly underestimate their real masses.

Key words: galaxies:halos — galaxies:elliptical and lenticular, cD — galaxies:individual (NGC 5128) — galaxies:kinematics and dynamics — galaxies:stellar content

1 INTRODUCTION

Structural, kinematical, and chemical properties of stars in the outer regions of galaxies, their halos, provide vital clues to their global formation and evolutionary histories. Although the physical properties of stellar halos have been extensively investigated mostly for spiral (e.g., the Galaxy and the M31) and dwarf galaxies in the Local Group (e.g., Eggen, Lynden-Bell, & Sandage 1962; Mould & Kristian 1986; Norris 1986; Freeman 1987; Durrell, Harris, & Pritchet 1994, 2001; Pritchet & van den Bergh 1998; Reitzel, Guhathakurta, & Gould 1998; Grillmair et al. 1996; Chiba & Yoshii 1998; Davidge 2002), recent observations have started to reveal physical properties of stellar halos in giant elliptical galaxies, all of which are beyond the Local Group (e.g., Soria et al. 1996; Harris, Harris, & Poole 1999 hereafter referred to as HHP; Harris & Harris 2000, HH00; Harris & Harris 2002, HH02; Marleau et al. 2000; Rejkuba et al. 2002; Gregg et al. 2004). These data prompt us to investigate how the properties of stellar halos can be used to understand the formation of giant elliptical galaxies.

Beyond projected radii of \(\sim 2R_e\), it becomes very diffi-
cult to study the integrated properties of stars in ellipticals because of the low stellar surface brightness. Hence, studies of stellar halos tend to rely on resolving individual stars or star clusters. While there are significant observational difficulties in revealing the three-dimensional structure and kinematics of halo red giants and AGB stars, it has been possible to use color-magnitude diagrams to derive their metallicity distribution function (hereafter MDF) and constrain the past star formation and chemical evolution histories of their host elliptical galaxies (e.g., HHP; HH00, HH02). Kinematic properties of these stars, however, which can contain vital clues to both structure and formation of ellipticals, are still extremely difficult to obtain. Furthermore, these previous observations have difficulties in deriving global stellar halo distributions, which are also considered to have valuable information on the past merging histories of galaxies (e.g., fossil tidal streams), mainly because the halo fields investigated cover only a minor portion of the entire halo.

Planetary nebulae (PNe) are a valuable complement to integrated light and red giant studies. They are powerful tools for studying the dynamical states of elliptical galaxies, because we can more readily identify PNe through their bright [O III] emissions lines and typically measure their radial velocities to an accuracy of \( \sim 15 \text{ km s}^{-1} \) (e.g., Peng et al. 2004a, PFF04a). Spectroscopic observations of the radial velocities of PNe in several nearby elliptical galaxies therefore have succeeded in deriving global mass distributions and velocity fields of these galaxies (Ciardullo et al. 1993; Hui et al. 1995; Arnaboldi et al. 1998; Mendez et al. 2001; Romanowsky et al. 2003; Napolitano et al. 2004; PFF04a). For example, kinematic information of PNe in the stellar halo of NGC 5128 at radii up to \( \sim 80 \) kpc allows the authors to derive the zero velocity curve (ZVC) in the two-dimensional velocity field of the PNS and thereby to discuss the triaxial shape of the mass distribution of this galaxy (PFF04a). This observed diversity in kinematics of PNSs is providing fresh clues to the origin of early-type galaxies. (Romanowsky et al. 2003; PFF04a).

In spite of this importance of PNe studies in elliptical galaxies, only a few theoretical and numerical attempts have been made to discuss dynamical properties of PNSs in elliptical galaxies. For example, using kinematical data up to \( \sim 6R_e \) for an heterogeneous sample of elliptical galaxies, Napolitano et al. (2004) derived the dependences of the radial gradients of the mass-to-light-ratios on the \( B \)-band magnitude of the galaxies and thereby discussed whether the derived dependences can be consistent with elliptical galaxy formation models based on a \( \Lambda \)CDM model. However, PNSs provide a very rich data set from which to study ellipticals. In particular, we are interested in exploring the 2D distributions of structural and kinematical properties of PNSs, which can provide some vital clues both to the triaxial shapes of the global mass distributions of galaxies and to their formation processes. The origin of 2D structural and kinematical properties of PNSs extending to the outer halo regions of elliptical galaxies remains unclear. Furthermore providing theoretical predictions on dynamical properties of PNSs will help to interpret the properties of PNSs that will be obtained in future systematic observations for elliptical galaxies.

The purpose of this paper is thus to investigate structural and kinematical properties of PNSs of elliptical galaxies based on numerical simulations. In order to elucidate the origin of the observed properties of the PNSs, we adopt the merger scenario (Toomre 1977) in which elliptical galaxies are proposed to be formed by major merging of two spiral galaxies. The present numerical investigation is two-fold as follows. We first describes radial profiles of structural and kinematical properties of PNSs and two-dimensional (2D) velocity fields of PNSs in elliptical galaxies and their dependences on model parameters. We then compare the simulated kinematics of the PNSs with the corresponding observations for NGC 5128 and thereby try to provide the best model for the PNS in NGC 5128 and discuss advantages and disadvantages of the model in explaining the kinematics of the PNS self-consistently. The essential reason for our choice of the NGC 5128 PNS is that PFF04a have recently investigated radial velocities of the NGC 5128’s 780 PNe (among 1141 PNe), which represents the largest kinematical study of an elliptical galaxy to date and thus can be compared with our simulations in the most self-consistent manner. Furthermore, the present study is complimentary to those by Bekki et al. (2003, BHH03) and Beasley et al. (2003) which numerically and semi-analytically investigated the MDF of the stellar halo of NGC 5128 but did not investigate the dynamical properties.

In the present paper, we mainly investigate structural and kinematic properties of PNSs for a large radial extent in elliptical galaxies (\( 0 \leq R \leq 10R_e \)), which include the outer faint stellar halos and the main bodies of the galaxies. Although previous numerical simulations investigated spatial distributions and the line-of-sight velocity distributions of stars in elliptical and S0 galaxies formed from merging for \( R < 2.5R_e \) (e.g., Bendo & Barnes 2000; Cretton et al. 2001; Naab & Trujillo 2005), they did not investigate the dynamical properties for the outer halo regions of elliptical galaxies. Therefore, the present numerical results on the dynamical properties of the outer stellar halos including PNe (\( 5R_e < R < 10R_e \)) may provide new clues to elliptical galaxy formation. Physical properties of these halo stars may well have fossil information on angular momentum redistribution of stars (or conversion from galactic orbital angular momentum into intrinsic angular momentum) which is an essential physical process of galaxy merging. We therefore can expect that dynamical properties of stellar halos, which can be provided by studies of PNSs, may depend strongly on physics of galaxy merging. Through the course of this paper, we thus interpret our simulations in the context of the capabilities of present-day PN surveys in order to facilitate the comparison between theory and observations.

The plan of the paper is as follows: In the next section, we describe our numerical models for the formation of PNSs extending to the outer halo regions in galaxy mergers. In §3, we present the numerical results mainly on the final 2D distributions of structural and kinematical properties in merger remnants (i.e., elliptical galaxies) for variously different merger models. In §4, we compare the simulated results of PNSs with observations of the PNS in NGC 5128 (Cen A). In §5, we discuss whether physical properties of stellar halos can give any constraints on galaxy formation, based on the present numerical results. In this section, we also discuss possible different properties of PNSs in galaxies with different Hubble types. We summarize our conclusions in §6.
2 MODEL

2.1 Merger models

We investigate the dynamical evolution of fully self-gravitating galaxies composed of stars and dark matter via collisionless numerical simulations carried out on a GRAPE board (Sugimoto et al. 1990). Since our numerical methods for modeling dynamical evolution of galaxy mergers have already been described by Bekki & Shioya (1998) and by BHH03, we give only a brief review here. The total mass and the size of a disk of the merger progenitor spiral are $M_d$ and $R_d$, respectively. Henceforth, all masses and lengths are measured in units of $M_d$ and $R_d$, respectively, unless specified. Velocity and time are measured in units of $v = (GM_d/R_d)^{1/2}$ and $t_{\text{dyn}} = (R_d^3/GM_d)^{1/2}$, respectively, where $G$ is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_d = 6.0 \times 10^{10} M_\odot$ and $R_d = 17.5 \text{ kpc}$ as a fiducial value, then $v = 1.21 \times 10^3 \text{ km/s}$ and $t_{\text{dyn}} = 1.41 \times 10^8 \text{ yr}$, respectively. The merger progenitor spiral is composed of a dark matter halo, a stellar disk, a stellar bulge, and a stellar halo.

The mass ratio of the dark matter halo to the stellar disk in a disk model is fixed at 10 for all models. We adopt $m_d = 0.6$ in our units for $m_d$. The orbital angular momentum ($L_x$) is 6.0 in our units for $L_x$. The pericentre distance ($r_p$) and the orbital eccentricity ($e_p$) are assumed to be free parameters which control orbital angular momentum and energy of the merging galaxies. For most merger models, $r_p$ and $e_p$ are set to be 1.0 (in our units) and 1.0, respectively. The spin of each galaxy in a merging and galaxy is specified by two angles $\theta_i$ and $\phi_i$ (in units of degrees), where the suffix $i$ is used to identify each galaxy. Here, $\theta_i$ is the angle between the $z$-axis and the vector of the angular momentum of the disk, and $\phi_i$ is the azimuthal angle measured from $x$ axis to the projection of the angular momentum vector of the disk onto the $x$-$y$ plane.

The total masses of elliptical galaxies can be underestimated, if kinematical properties of PNSs are used for the mass estimation (e.g., Dekel et al. 2005). We also find that the masses of ellipticals can be significantly underestimated if radial velocity profiles of PNSs are used under the assumption of the virial theorem. We just briefly discuss this point in the discussion section §5.3, because our main focus is on 2D density and velocity fields of PNSs in elliptical galaxies.

2.2 Main points of analysis

We mainly investigate 2D density and velocity fields of PNSs and compare the results with the corresponding observations in a fully self-consistent manner. We accordingly use Gauss-
sian smoothing similar to that adopted in observations (e.g., PFF04a) in order to derive smoothed density and velocity fields of the simulated PNSs. The details of the methods to derive the smoothed fields are given in the Appendix A. Figure 1 shows how the smoothed PNe density field looks like for the stellar halo consisting only of 1000 discrete stars in an isolated disk model M1 (viewed from face-on).

Although the MDFs of stellar halos (thus PNe) can give some constraints on any theory of elliptical galaxies formation (e.g., HHH02; BHH03), we do not intend to discuss them in this paper. This is firstly because (1) the importance of the MDFs have been already discussed in previous papers (e.g., BHH03) and secondly because there is no currently available data set of the MDFs of PNe for nearby giant elliptical galaxies. Instead, we mainly investigate (1) radial profiles of projected PNe number densities, (2) 2D fields of line-of-sight velocity (\(V_{\text{los}}\)) and velocity dispersion (\(\sigma\)), (3) rotation curve profiles (\(V_{\text{rot}}\)), and (4) radial profiles of \(\sigma\) and \(V_{\text{rot}}/\sigma\), for the PNSs of merger remnants. Although we investigated the above four points for 32 merger models with different \(m_2\) and orbital configurations, we show the results of 9 representative models among them. Table 2 summarizes the model parameters used for these 9 models. We show the results of the models at \(T = 4.5\) Gyr (at final time step), where the time \(T\) represents time that has elapsed since the merger progenitor disks begin to merge.

We firstly show the results of the “fiducial model”, model M2, which show typical behaviors of stellar halo (thus PNS) formation in major galaxy merging (§3.1). The results of this model can be regarded as generic ones for elliptical galaxies formed from major merging. Secondly we show the parameter dependences of the results in §3.2 with special emphasis on the dependence of projected PNe number densities and the 2D velocity fields on orbital configuration and \(m_2\). Thirdly, we present the best model which can reproduce the most reasonably well a number of dynamical properties of the PNS observed in NGC 5128 (§4.1). It should be stressed here that the best model is the best model among the present 32 models, thus is not the one which reproduce all of the observed properties of the PNS fully self-consistently. We try to understand advantages and disadvantages of the present best model by comparing it with observations, and discuss whether (and how) physical effects that are not included in the present models (e.g., star formation) can be important for more successful reproduction of the observations. The best model is model M9 with \(a_p = 1.0, r_p = 0.05\) in our units, \(\theta_1 = 0, \theta_2 = 80, \phi_1 = 0, \) and \(\phi_2 = 0, \) and \(m_2 = 0.5\) (The orbital configuration is hereafter referred to as “PO”).

3 RESULTS

3.1 The fiducial model

3.1.1 Density fields

Figure 2 shows the projected stellar mass distributions of the fiducial model M2 at \(T = 4.5\) Gyr in which the final merger remnant shows \(R_e\) of 5.2 kpc, \(L_B = 3.7 \times 10^{10}\) L\(_\odot\), and \(N_{\text{PNe}} = 350\) within ~ 5\(R_e\). The merger remnant does not show any clear signs of stellar substructures (i.e tidal tails and plumes) in its halo region for the two projections owing to the apparently completed dynamical relaxation by this time (\(T = 4.5\) Gyr). It is also possible that the much less remarkable substructures are due to the adopted smaller particle number (an order of ~ 10\(^5\)). The outer stellar halo (\(R > 5R_e\)) in the edge-on view is more spherical (\(\epsilon \sim 0.3\)) than the main body of the elliptical (\(\epsilon \sim 0.2\) at \(R \sim 2R_e\)).
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Figure 3. The 2D PNe density field for the face-on view (left) and the edge-on view (right) in the fiducial model at $T = 4.5$ Gyr. The 2D fields are produced based on the stellar mass distributions shown in Figure 2.

Figure 4. Radial profiles of the projected PNe number densities ($\rho_{\text{PNe}}$) for the fiducial merger model M2 (thick) and the isolated disk model M1 (thin). Note that the elliptical galaxy formed in M2 shows significantly higher $\rho_{\text{PNe}}$ in its outer region ($R > 20$ kpc) compared with the spiral in M1.

Figure 5. The 2D velocity fields for the face-on view (left) and the edge-one view (right) for the fiducial model M2 at $T = 4.5$ Gyr.

Figure 6. The same as Figure 5 but for the 2D velocity dispersion fields.

The outer stellar halo is slightly more flattened than the dark matter halo with $\epsilon = 0.15$ at $R = 5R_e$ in the edge-on view and the major-axis of the stellar halo nearly coincides with that of the dark matter halo. The isophotal shape of this remnant formed from purely collisionless major galaxy merging can show the negative sign of the $a_4$ parameter (e.g., Bekki & Shioya 1997), and thus this remnant can be morphologically identified as a boxy elliptical galaxy.

Figures 3 and 4 describe the 2D density fields of the PNS in the elliptical and the radial profile of the PNe distribution, respectively. Owing to the adopted assumption of constant $\alpha_{\text{PNe}}$ (i.e., constant luminosity-specific number densities of PNe), the 2D density fields of the PNS follows the stellar density ones of the elliptical and therefore shows a more flattened shape in the edge-on view. The radial density profile is best fitted to the power-law with the exponent of $-2.7$ for $0 \leq R \leq 40$ kpc ($\sim 8R_e$), which is slightly steeper than the observed slope of $-2.5$ for the PNS of NGC 5128 (PFF04a). The projected PNe density of the elliptical in its outer stellar halo ($R > 5R_e$) is more than two orders magnitudes higher than those of the merger progenitor spirals, though the PNe densities in the central regions of galaxies are not so different between the elliptical and the spirals.

The formation of such a high density stellar halo is demonstrated to be closely associated with redistribution of disk stars through tidal stripping of the stars during major galaxy merging (BHH).

Figure 5 shows the 2D fields of $V_{\text{los}}$ (i.e., line-of-sight velocity) of the merger remnant for $0 \leq R \leq 35$ kpc ($\sim 7R_e$) in the face-on and edge-on views. Clearly, the PNS shows a significant amount of rotation ($\sim 100$ km s$^{-1}$) along its major axis (i.e., the X-axis) for the edge-on view. Given the fact that the stellar halos of the merger progenitor spirals are assumed to have no net rotation, the rotation in the outer halo of the elliptical can be considered to be obtained during angular momentum redistribution of major galaxy merging. This angular momentum transfer processes have been already well discussed in previous papers (e.g., Barnes 1998 for a review).

The axis of rotation in the edge-on view however does not coincide with the minor axis of the PNe density field shown in Figure 3: Radial velocity gradient can become maximum if we measure it along a line connecting two points (X,
The radial profile of the rotation curve $V_{\text{rot}}$ (upper) and the velocity dispersion $\sigma$ (lower) for the dark matter halo (thick) and for stars (thin) in the fiducial model M2 at $T = 4.5$ Gyr. $V_{\text{rot}}$ and $\sigma$ are estimated for the model projected onto the X-Y plane (i.e., the face-on view). The methods to derive $V_{\text{rot}}$ and $\sigma$ and their error bars are described in detail in the Appendix A.

$Z = (−35, 35)$ and $(35, −35)$ kpc for the edge-on 2D velocity field. Minor axis rotation can be clearly seen in the outer halo region of the elliptical for the edge-on 2D velocity field and the velocity variation along the minor axis (i.e., the $Z$-axis) is complicated. Also it should be stressed that the edge-on 2D field has several regions with large absolute magnitudes of $V_{\text{rot}}$ (e.g., $(X, Z) = (35, −8)$ and $−20, 3$ kpc). Such inhomogeneity in the velocity space may indicate that dynamical relaxation is not completely ended in a real term even a few Gyr after the coalescence of two spirals in the fiducial model: Fossil evidences of past violent relaxation can be proved in velocity structures of outer stellar halos in elliptical galaxies.

The face-on 2D velocity field also shows rotation along the major and the minor axes of the projected density distribution of the PNS, though the rotation in the outer stellar halo for the face-on 2D field is less remarkable compared with the edge-on one. The global appearance of the face-on 2D velocity field is smoother than that of the edge-on one and complicated velocity variation along the minor axis of the PNS can not be clearly seen. Thus these results imply that (1) PNSs in elliptical galaxies can show a significant amount of rotation in their outer halo regions, (2) minor-axis rotation of PNSs is one of important characteristics of elliptical galaxies, and (3) the 2D velocity fields can be different for different viewing angles.

As shown in Figure 6, both the face-on and the edge-on 2D velocity dispersion ($\sigma$) fields show (1) higher velocity dispersion in the inner regions of the elliptical, (2) a shallower gradient of velocity dispersion along the major axis (i.e., the $X$-axis) compared with that along the minor one, and (3) globally flattened shapes, in particular, in outer stellar halo regions. These three can be regarded as important kinematical characteristics of stellar halos (PNSs) in elliptical galaxies formed by major merging. The flattened velocity dispersion fields are due to anisotropic velocity dispersion in the triaxial mass distribution of the elliptical galaxy in this fiducial model. The dispersion field appears to be more homogeneous in the face-on view than in the edge-on one, though some remarkable substructures that can result from yet incomplete dynamical relaxation of this system can be seen in both projections. The results shown in Figures 4, 5, and 6 clearly suggest that even if the 2D density fields of PNSs appear to be quite regular and axisymmetric, their 2D velocity and velocity dispersion fields can be more inhomogeneous and less axisymmetric: The kinematic properties of a stellar halo in an elliptical galaxy can provide some evidences of the past dynamical processes of its formation, if penetrative analysis of such “fossil record” properties can be done.

Figures 7 and 8 show the radial profiles of rotational velocities ($V_{\text{rot}}$) and velocity dispersions ($\sigma$) for the dark matter halo and the stellar components (i.e., PNe) in the elliptical of the fiducial model. It is clear from these figures that (1) the dark matter halo shows a larger velocity dispersion (by a factor of $1.1 – 2.0$, depending on radius) than the PNe, (2) the PNe shows a significant amount of rotation $40 – 60$ km s$^{-1}$ in the entire halo region $(R > 5R_e)$ of the elliptical for the edge-on view, (3) the maximum $V_{\text{rot}}$ in the halo region is higher in the edge-on view than in the face-on one, (4) the radial gradient of $V_{\text{rot}}$ is quite different between different projections, and (5) the radial velocity dispersion profiles (e.g., the central $\sigma$ and the gradient) do not differ significantly with each other. The above result (1) strongly
suggests that we can significantly underestimate the total mass of an elliptical galaxy, if we use only the velocity dispersion data of the PNS and thereby derive the total mass based on the scalar virial theorem in which the mass is linearly proportional to the product of \( R_e \) and \( \sigma \): We need to derive the total mass of an elliptical by using both dispersion and rotation data of the PNS. The result (2) is consistent with previous numerical simulations (e.g., Heyl et al. 1996).

Given the fact that the radial dispersion profile of the PNS decreases with radius in the fiducial model, the above result (2) means that the PNS shows a higher value of \( V_{\text{rot}}/\sigma \) in the outer halo of the elliptical. (e.g., \( V_{\text{rot}}/\sigma \) of \( \sim 0.7 \) at \( R \approx 5R_e \)). This larger \( V_{\text{rot}}/\sigma \) also results from the redistribution of angular momentum of disks stars during major merging (i.e., conversion of initial orbital angular momentum of merger progenitor disks into final intrinsic one of the merger remnant), as explained for Figure 5. This result suggests that larger \( V_{\text{rot}}/\sigma \) in the outer stellar halo of an elliptical galaxy can be a fossil evidence that the elliptical was formed from major galaxy merging. The derived PNS with larger \( V_{\text{rot}}/\sigma \) in the outer halo region is in a striking contrast to the Galactic stellar halo with little rotation (e.g., Freeman 1987), which implies that stellar halo kinematics can be significantly different between spirals and ellipticals. Recent numerical simulations based on the currently favored cold dark matter (CDM) theory of galaxy formation have shown that the Galactic stellar halo with little rotation is formed at high redshift (\( z > 1 \)) by dissipative and dissipationless merging of smaller subgalactic clumps and their resultant tidal disruption in the course of gravitational contraction of the Galaxy (Bekki & Chiba 2000, 2001). Thus the above result (2) implies that differences in formation processes of stellar halos between different types of galaxies (e.g., spirals vs ellipticals) can be reflected on the stellar halo kinematics. The above results (3) - (5) imply that radial profiles of rotational velocities of PNSs in elliptical galaxies depend more strongly on viewing angles than those of velocity dispersion.

Figure 9 describes how \( V_{\text{rot}}/\sigma \) and \( V_{\text{rot}}/\sigma_0 \) depend on radius in the PNS of the fiducial model for 12 representative projections. There can be seen a trend of increasing \( V_{\text{rot}}/\sigma \) and \( V_{\text{rot}}/\sigma_0 \) with increasing radius, though the radial profiles rise and fall with radius significantly. The higher \( V_{\text{rot}}/\sigma \) and \( V_{\text{rot}}/\sigma_0 \) of the PNS in the outer halo region of the elliptical for most of the projections (viewing angles) means that the PNS in the outer halo region is the most likely to...
be observed as being strongly supported by rotation. Figure 10 shows that a PNS with higher $V_{\text{rot}}/\sigma$ at $R = 2R_e$ is more likely to have higher $V_{\text{rot}}/\sigma$ at $R = 5R_e$: There is a correlation in stellar kinematics between the main body and the stellar halo of the elliptical, though the correlation is weak. Figure 10 also shows a stronger correlation between $V_{\text{rot}}/\sigma_0$ at $R = 2R_e$ and $V_{\text{rot}}/\sigma_0$ at $R = 5R_e$. The derived correlations imply that if elliptical galaxies are formed from major galaxy merging, the kinematic of their main bodies derived from integrated absorption spectra (for $R < 2R_e$) can be correlated with that of their outer stellar halos derived from radial velocity fields of PNe (for $R > 5R_e$). The predicted “halo-host kinematic correlation” can be tested by future extensive systematic studies of PNe kinematics for elliptical galaxies with already known kinematics of the main bodies.

3.2 Parameter dependences

3.2.1 Orbital configurations

The dependences of dynamical properties of PNSs in elliptical galaxy formed by major galaxy merging with $m_2 = 1.0$ on orbital configurations of the merging are described as follows.

(1) Irrespective of orbital configurations, the radial profiles of the projected PNe number densities in PNSs can be fitted to the power-law profile for the entire halo regions of their host elliptical galaxies. The simulated PNSs of ellipticals in all models in the present study have the mean PNe densities more than an order of magnitude higher than those of stellar halos of their merger progenitor spirals. The central values of the projected PNe number densities do not depend on orbital configurations. These results suggest that structural properties of outer PNSs (thus stellar halos) can be significantly different between spirals and ellipticals.

(2) Most of PNSs can show a significant amount of rotation in the outer halo regions ($R > 5R_e$) of their host elliptical galaxies, though the maximum values of the rotational velocities ($V_{\text{rot}}$) depend on the viewing angles of the ellipticals. The 2D velocity fields of most PNSs shows minor-axis rotation in their halo regions, as seen in the main bodies ($R < 2R_e$) of elliptical galaxies (e.g., Bendo & Barnes 2000). The details of the 2D velocity field of PNSs depend strongly on orbital configuration of galaxy merging. For example, the PNS of the elliptical formed from a retrograde-retrograde merging (model M4) shows a more inhomogeneous and more complicated 2D velocity field in its edge-on view than that from a prograde-prograde merging, though there are no significant differences in the 2D fields between the two for the face-on view (See Figures 11 and 12 and compares the two velocity fields with each other). The 2D velocity dispersion fields does not so strongly depend on orbital configurations than the 2D velocity ones.

(3) $V_{\text{rot}}/\sigma$ of PNSs are more likely to be higher in
the outer halo regions of elliptical galaxies ($R > 25$ kpc corresponding to $\sim 5 R_e$) than in the central regions $R \sim 5$ kpc, as shown in Figure 13. This result suggests that PNs of elliptical galaxies are likely to show rotational kinematics in their outer halo regions, if they are formed from major galaxy merging. $V_{rot}/\sigma_0$ (rotation curve normalized to the central velocity dispersion $\sigma_0$) has the radial dependence similar to $V_{rot}/\sigma$ (Figure 13). The flat rotation curve of $V_{rot}/\sigma_0$ seen in most of the models for their outer halo regions ($R > 25$ kpc) suggests that such flattened shapes of $V_{rot}/\sigma_0$ is one of generic trends of stellar halos kinematics in elliptical galaxies formed from major merging.

(4) There is a weak correlation between $V_{rot}/\sigma$ at $R = 2 R_e$ and $V_{rot}/\sigma_0$ at $R = 5 R_e$ in the sense that PNs with larger $V_{rot}/\sigma$ at $R = 2 R_e$ are more likely to show larger $V_{rot}/\sigma_0$ at $R = 5 R_e$ (See Figure 14). This result suggests that kinematics of outer stellar halos in elliptical galaxies can correlate with that of their main bodies, if elliptical galaxies are formed from major merging. Similar trend can be seen for $V_{rot}/\sigma_0$, which implies that elliptical galaxies with the main bodies rotating more rapidly are likely to show a larger amount of rotation in their outer halo regions. The derived two correlations, though weak, can be used as theoretical predictions that should be compared with future observations of PNe kinematics in elliptical galaxies.

(5) These radial differences of $V_{rot}/\sigma$ characteristics of PNs of elliptical galaxies formed by major merging (See Figures 13 and 14) can be derived only if we can obtain kinematical data for outer halo components ($R \sim 5 R_e$) of elliptical galaxies. This implies that we need to investigate observationally and theoretically kinematical properties of stellar halos beyond $2 R_e$ to give some constraints on elliptical galaxy formation and thus that PNe kinematical studies are ideal for this purpose.

3.2.2 Mass ratios ($m_2$)

The dependences of dynamical properties of PNs in merger remnants on $m_2$ are described as follows.

(1) The projected PNe number densities $\rho_{PN}$ ($\log_{10}(N/kpc^2)$) are globally lower in the remnants with smaller $m_2$, in particular, for the outer parts ($R > 5 R_e$ corresponding to $\sim 25$ kpc) of PNs (See Figure 15). This means that more flattened elliptical galaxies are more likely to show lower $\rho_{PN}$, because the morphological properties of the host galaxies formed from these mergers with lower $m_2$ show more flattened intrinsic shapes. The power-law slope of the density profile $\rho_{PN}$ ($\log_{10}(N/kpc^2)$) does not strongly depend on $m_2$ for $R \leq 5 R_e$, however, there is a clear sign of steeper slope in the model with $m_2 = 0.1$ for $R > 5 R_e$ owing to the rather low PNe density there. The result implies that the $\rho_{PN}$ is steeper in Es formed from major galaxy merging (e.g., $m_2 > 0.3$) than in S0s from unequal-mass/minor galaxy merging with ($0.1 < m_2 < 0.3$).

(2) The kinematics of PNs in E/S0s formed from galaxy merging with lower $m_2$ show more rapid rotation, larger maximum values of $V_{rot}$, and steeper radial gradients of $V_{rot}$ for $R < 2 R_e$ (See Figure 16). Given the fact that
remnants of galaxy merging with smaller $m_2$ show more flattened shapes, this result suggests that more flattened E/S0 have higher $V_{\text{rot}}$ and steeper radial $V_{\text{rot}}/\sigma$ gradients. Irrespective of $m_2$, the outer regions of PNSs ($R \geq 5R_e$) can show high $V_{\text{rot}}$ and thus large $V_{\text{rot}}/\sigma_0$, owing to the nearly flat rotation curve and the radially decreasing $\sigma$ (See Figure 17). This suggests that stellar halos in E/S0s formed by galaxy merging show different kinematics compared with that of the Galaxy with little rotation.

3) The larger values of $V_{\text{rot}}/\sigma$ in the PNS for edge-on projections (i.e., $X-Z$ and $Y-Z$) in S0s formed from unequal-mass merging suggests that rotational terms in Jeans equations should be considered when we estimate total masses of S0s using PNe data (See Figure 16). The small values of $V_{\text{rot}}/\sigma$ for the face-on projection (i.e., $X-Y$) imply that the total mass of an S0 (thus mass-to-light-ratio) can be significantly underestimated if it is viewed from face-on and if the mass is estimated by the Jeans equation with correction terms of rotation (and if the projected central velocity dispersion does not depend on the viewing angle). The observed small $M/L$ in some early-type galaxies (e.g., in NGC 3379) could be due to this viewing angle effect.

4 COMPARISON WITH OBSERVATIONS OF NGC 5128 PNE SYSTEMS

4.1 Selection of the best model

We present the results of one of the best models (model M9) in which the observed structural and kinematical properties of the PNS in NGC 5128 (PFF04a) are the most self-consistently reproduced. We select this best model among the 32 models investigated in the present study by checking whether the following five fundamental observational results (e.g., Israel 1998; PFF04a) can be reproduced reasonably well in each model: (1) $R_e = 5.2$ kpc, $M_1$ (total luminous mass) $= 1.4 \times 10^{11}$ $M_\odot$ (for $M_1/L_B = 3.5$), and spherical appearance of the elliptical galaxy, (2) the projected PNe number density of $\rho_{\text{PNe}}$ ($\log_{10}(N/kpc^2)$) $\approx 1.0$ at $2R_e$ and the slope of the power-law profile similar to $-2.5$, (3) the rotation curve that rises till $R \approx 2R_e$ and becomes flat at $R > 2R_e$, and the central velocity dispersion $\sigma_0$ of $\approx 140 \pm 10$ km s$^{-1}$, and (5)
the 2D velocity field showing both minor and major axes rotation with the zero velocity curve/contour (ZVC) twisting significantly.

Owing to the purely collisionless nature of the present simulations, we can match any model to the above observation (1) by rescaling the size and the mass of the simulation. Therefore, the above (2) - (5) constraints can be used in selecting the best possible model in the present study. Major merger models with $m_2 = 1.0$ can explain the above (2), (4), and (5) reasonable well, however they have difficulties in explaining (3) owing to slowly rising $V_{rot}$ with smaller maximum values of $V_{rot}$. Unequal-mass merger models with $m_2 = 0.1 - 0.3$ can become early-type E/S0s, however, they are very flattened in shapes, strongly supported by rotation, and have 2D velocity fields that are not similar to the observed ones. These models accordingly can not explain the above (1), (4), and (5) in a fully self-consistent manner and thus can not be regarded as the best model. Thus one of the best models can be unequal-mass mergers with $m_2$ of somewhere between 0.3 and 1.0 (viewed from a certain direction): However, it should be stressed here that we possibly could miss out the major merger model with $m_2 = 1.0$ that can explain the above five points self-consistently, owing to the limited number of the simulated models.

The best model for which we show the results below is the model 9 with $m_2 = 0.5$ in which a highly inclined orbital configuration and a smaller pericentre distance are assumed. We investigate dynamical properties of the PNS in this model at $T = 4.5$ Gyr when the remnant is dynamically well relaxed to show regular distributions of PNe both in the 2D distribution of the projected number density and in the radial one (See Figures 17 and 18). This model with smaller pericenter distance and a highly inclined disk with respect to the orbital plane can form stellar shells and gaseous rings perpendicular to the major axis of the merger remnant if gaseous dissipation is included (Bekki 1997, 1998a). Thus, our future more sophisticated model with gaseous dissipation and star formation will be capable of explaining the observed HI distribution perpendicular to the photometric major axis and the outer shells as well as the above five observations. Dynamical properties of globular cluster systems and fine structures observed in NGC 5128 (Peng et al. 2002; 2004b, c) will be discussed in the best model(s) of our future studies (Bekki & Peng 2005, in preparation).

4.2 Advantages and disadvantages of the best model

Figures 19 presents the comparison between the simulated 2D velocity field of the PNS of the best model and the observed one. In order to match the observation with the simulation, the observed coordinate $-X$ ($Y$) for the PNS in NGC 5128 (PFF04a) is set to represent $+X$ ($Z$) in Figure 19 (and 20, 21) for convenience. The best model is consistent with the observation at least qualitatively in the sense that it shows (1) strong major-axis rotation extending to 35 kpc ($\sim 7 R_e$), (2) weaker but significant rotation along the
minor axis, and (3) the line of zero velocity (referred to as zero velocity curve, ZVC) both misaligned and twisted with respect to the major axis of the PNe distribution. Figure 20 more clearly describes how the ZVC looks like in the 2D velocity field and whether it is consistent quantitatively with the observed ZVC. The observed ZVC can be parameterized as follows (PFF04a):

\[ Z = \frac{-X(0.125|X| + 5)}{\sqrt{(X^2 + 2.56)}} \]  

where \( X \) and \( Z \) are exactly the same as the coordinate \( X \) and \( Z \) in the simulations. As shown in Figure 20, the simulated ZVC starts twisting at \( Z \sim \pm 10 \) kpc whereas the observed ZVC starts twisting at \( Z \sim \pm 4 \) kpc. The direction of the simulated ZVC for \( |X| > 10 \) kpc is broadly consistent with the observed one, though the simulated ZVC is more aligned with the minor axis of the 2D PNe distribution (shown in Figure 19) compared with the observed one for \( |X| \leq 10 \) kpc. These less successful reproduction of the model suggests that (1) some physics which are not included in the present study (e.g., gaseous dissipation and star formation) should be considered to reproduce fully self-consistently the observations and (2) we need to explore wider sets of model parameters (e.g., merger orbits) to find a fully self-consistent model.

Figure 21 presents the comparison between the simulated 2D velocity dispersion field of the PNS and the observed one (PFF04a). The simulation is consistent broadly with the observation in the sense that (1) it shows an inner flattened shape in the 2D velocity dispersion field and (2) radial gradient of velocity dispersion along the minor axis is steeper than that along the major axis. Interestingly, the observation shows an isolated region with high velocity dispersion (\( \sim 200 \text{ km s}^{-1} \)) around \((X, Z) = (15, -5) \) (kpc). An apparently isolated region with moderately high velocity dispersion (\( \sim 120 \text{ km s}^{-1} \)) can be discernibly seen also in the simulation around \((X, Z) = (25, -2) \) (kpc). Although it is not so clear whether the presence of such local, dynamically hot regions in the 2D velocity dispersion fields have some physical meanings of elliptical galaxy formation, more extensive comparison between observations and simulations in terms of the locations of the isolated, dynamically hot regions should be made to determine the best model after a larger set of PNe kinematical data become available, in particular, for the regions with \( X > 0 \) kpc and \( Z < -10 \) kpc.

Figure 22 demonstrates that the best model can explain the observed rotation curve \( (V_{\text{rot}}) \) profile reasonably well for \( R < 3 \) kpc and \( 10 < R_{50} \) kpc. However there is a significant difference in \( V_{\text{rot}} \) profiles between the observation and the simulation for \( R \sim 5 \) kpc: The observational rotation curve rises more rapidly than the simulated one for the inner region of NGC 5128. The radial profile of velocity dispersion \( (\sigma) \) in the model is systematically higher (a factor of 1.2 at \( R \approx 2R_e \)) than the observed one. We suggest that these less successful reproduction of the best model for \( V_{\text{rot}} \) around \( R = 5 \) kpc and the \( \sigma \) profile is due to the model’s not including PNe formation from gas: All PNe are assumed to originate from collisionless old stellar disks. We can expect that if PNe can form from gas, new PNe have a larger amount of rotation and smaller amount of random kinetic energy owing to efficient energy dissipation of random kinematic energy during galaxy merging. We thus suggest that our future more sophisticated model with gaseous dissipation can more successfully reproduce the observed radial profiles of \( V_{\text{rot}} \) and \( \sigma \).

5 DISCUSSION

5.1 Constraints on galaxy formation from stellar halo kinematics

PFF04a have revealed that the PNS of NGC 5128 has a significant amount of rotation with \( V/\sigma \) between 1 to 1.5 in its outer stellar halo region \((R > 5R_e)\). The present study has shown that outer stellar halos in most of major merger models have a significant amount of rotation and thus suggested that a rotating stellar halo seen in NGC 5128 is not just a special case but a rather general trend of elliptical galaxies, if ellipticals are formed by galaxy merging. The kinematics of PNSs in several elliptical galaxies have been investigated so far (Ciardullo et al. 1993; Hui et al. 1995; Arnaboldi et al. 1998; Mendez et al. 2001; Romanowsky et al. 2003; Napolitano et al. 2004; PFF04a) and found to show rotation in some of the ellipticals. Although these observational studies help the authors to provide a reasonable dynamical model (e.g., total mass of a galaxy) for each individual case, the total number of PNSs investigated is too small for them to make any robust conclusions on the general trend of kinematics in outer stellar halos \((R > 5R_e)\) of elliptical galaxies.

We suggest that extensive systematic studies of kinematical studies of PNe for \( 2R_e \leq R \leq 10R_e \) for a larger number of elliptical galaxies are doubtlessly worthwhile, because the kinematics of outer stellar halos can provide strong
of the Galaxy in the sense that the stellar halo of NGC 5128 are more metal-rich and more strongly rotating. These differences in stellar halo properties may well be remarkable and fundamental differences between spiral and elliptical galaxies, though extensive observational studies of PNe in spirals beyond the Local Group that can prove dynamical properties of the stellar halos have not been yet conducted. Although the MDF was investigated for the stellar halo of the edge-on S0 NGC 3115 (Elson 1997; Kundu & Whitmore 1998), systematic studies on the MDFs of stellar halos and dynamical properties of PNe in S0s have not been done yet. Thus future observational studies of structural and kinematical properties of PNe in spirals and S0s, combined with those ongoing for ellipticals, will provide a new clue to the origin of the Hubble sequence.

### 5.3 Mass Estimates

One ongoing field of study using PNe is the total mass of elliptical galaxies. Typically, analysis of this sort use the integrated rotation and velocity dispersion profiles of the PNe to derive a total mass within a given radius (e.g., PFF04a, Romanowsky et al. 2003, Méndez et al. 2001). As one can see from Figure 9, a single galaxy can have a wide range of rotation and dispersion profiles depending on the viewing angle, and this could plausibly lead to biases in the mass estimation. We test this by adopting the mass estimation procedure outlined in PFF04a, which uses the spherical Jeans equation and assumes an isotropic distribution of orbits. While this is a simple assumption, it is one that is typically used and there has yet to be any strong kinematic evidence that orbits in ellipticals are strongly anisotropic. When we fit the kinematic profiles of the major merger model from the face-on and edge-on views, we find that the face-on view gives a mass that is a factor of two lower than the edge-on view. The reason for this can be seen qualitatively in Figures 7 and 8 which shows that the rotation and velocity dispersion profiles are both lower for the face-one view.

Even more intriguing, the simulations consistently show that the dark matter is at a higher velocity dispersion than the stars. In fact, while the face-on view under-represents the mass relative to the edge-on view, both viewing angles underestimate the total mass. In order to estimate the total mass of a merger remnant from PNe kinematics and thereby discuss this point in a more quantitatively, we use the same method as those used by Hui et al. (1995) and PFF04a: We apply the spherical Jeans equation to the major-axis rotation and line-of-sight velocity dispersion profile (e.g., Figures 7 and 8) in a merger remnant (i.e., an elliptical galaxy) to derive the dynamical mass of the remnant (See PFF04a for more details on the methods of mass estimation from PNe kinematics).

Table 2 summarizes the actual masses of the simulated E/S0s within 45 kpc ($M_{T,A}$) and the masses estimated

| Model no. | Fitted mass ($M_{T,P}$) | Actual mass ($M_{T,A}$) | $M_{T,P}/M_{T,A}$ |
|-----------|-------------------------|-------------------------|-------------------|
| M1 (edge-on) | 1.7 x 10^{11} M⊙ | 8.6 x 10^{11} M⊙ | 0.20 |
| M1 (face-on) | 7.4 x 10^{10} M⊙ | 8.6 x 10^{11} M⊙ | 0.09 |
| M8 (edge-on) | 9.3 x 10^{11} M⊙ | 7.1 x 10^{11} M⊙ | 1.31 |
| M8 (face-on) | 1.5 x 10^{10} M⊙ | 7.1 x 10^{11} M⊙ | 0.02 |
from the simulated radial velocity dispersion profiles and the Jeans equation used in Peng et al. (2004a) within 45 kpc (3Mₚ,rots) for two interesting cases. Compared to the total amount of mass in the simulation, our simple mass estimation from the stellar data viewed edge-on (best case) underestimates the total mass within 45 kpc by a factor of 5. In one model for a minor/unequal-mass merger viewed face-on, the total mass is underestimated by a factor of 50 and requires no dark halo. If ellipticals result from these types of mergers, then this could be a very important consideration, especially considering that current mass estimates for ellipticals are surprisingly low. This matter warrants further investigation with a variety of different elliptical formation models. (Dekel et al. 2005 have recently discussed this problem with a complementary approach and also find masses can be underestimated). However, we point out that the supposedly low M/L recently measured are for intermediate-luminosity galaxies (e.g. NGC 3379 and NGC 5128) and not for all galaxies. If this “stellar kinematic bias” is the reason for anomalously low mass estimates, then it may be more pronounced in lower luminosity ellipticals, providing a clue to their formation histories.

6 CONCLUSION

We have numerically investigated structural and kinematical properties of PNSs in elliptical galaxies formed by galaxy merging in order to elucidate the origin of the observed physical properties of PNSs. We have mainly investigated the radial profiles of projected number densities, rotational velocities, and velocity dispersion of PNSs and the two-dimensional velocity fields of PNSs in elliptical galaxies. We also compared the simulated dynamical properties of PNSs with the corresponding observations of the PNS in NGC 5128 and thereby tried to provide the best merger model for the PNS in NGC 5128. We summarize our principal results as follows.

(1) The radial densities profiles of PNSs can be fitted to the power-law in the entire halo regions of elliptical galaxies formed from major merging (m₂ = 1.0). The projected PNe number densities (pPNₑ) at R ∼ 5Rₑ in elliptical galaxies are more than an order of magnitude higher than those of the halos of the merger progenitor spirals. These results do not depend strongly on the model parameters of major merging. The main reason for rather higher pPNₑ of PNSs is that a significant fraction (∼ 10%) of disk stars are stripped from the disks and redistributed in the halo regions during major merging. These results suggest that elliptical galaxies have higher PNe number densities (pPNₑ) in their halos than spiral ones.

(2) PNSs of elliptical galaxies formed from major merging can show a significant amount of rotation (Vₑot/σ > 0.5) in their outer halo regions (R > 5Rₑ). The derived rotation in the outer halos results from the angular momentum redistribution of disk stars during galaxy merging (i.e., conversion of orbital angular momentum of merging two spirals into the intrinsic one of the merger remnant). Vₑot/σ of PNSs in ellipticals are more likely to be larger in the outer parts than in the inner ones, though radial profiles of Vₑot/σ are diverse between different models. Vₑot/σ at 5Rₑ can weakly correlate with Vₑot/σ at 2Rₑ for the PNSs in such a way that PNSs with larger Vₑot/σ at 2Rₑ are likely to show larger Vₑot/σ at 5Rₑ. This result implies that the kinematics of outer stellar halos in elliptical galaxies can correlate with that of the main bodies.

(3) The two-dimensional (2D) fields of velocity and velocity dispersion of PNSs in elliptical galaxies formed by major merging are quite diverse depending on the orbital configurations of galaxy merging, the mass ratios of the progenitor spirals, and the viewing angles of the galaxies. For example, PNSs of ellipticals formed from prograde-prograde merging can show more rapid rotation along the major axes of the PNe density profiles in their 2D velocity fields compared with the retrograde-retrograde ones. For most of the models, the 2D velocity fields show minor axis rotation in the outer halo regions of elliptical galaxies. It is doubtlessly worthwhile for future observational studies to systematically investigate dynamical properties of PNS for a larger number of elliptical galaxies and thereby to confirm whether the predicted uniformity and diversity in the 2D velocity fields of PNSs can be seen in elliptical galaxies.

(4) ρPNe of PNSs are more likely to be lower in E/S0s formed from galaxy merging with smaller mass ratios (e.g., m₂ = 0.3, i.e., unequal-mass merging). Furthermore, PNSs in the remnants of mergers with smaller m₂ have more flattened shapes and a larger amount of rotation (Vₑot) both in their main bodies and in their outer halos. Therefore these results suggest that more flattened E/S0s are more likely to show both lower ρPNe and higher Vₑot (for a given luminosity range of E/S0s). This predicted correlation can be readily confirmed in future observations of PNSs.

(5) The observed kinematical properties of the PNS in NGC 5128 (e.g., Vₑot/σ between 1 and 1.5 and minor axis rotation) can be broadly consistent with the present best model with m₂ = 0.5, a small impact parameter, and highly inclined initial disks (similar to a polar-orbit). The observed “kink” in the zero velocity curve (ZVC) of the 2D velocity field of the PNS in NGC 5128 can be reproduced reasonably well, though the location where ZVC begins to twist is different between the best simulation model and the observation. Some disadvantages of the present best model in explaining self-consistently the observed kinematics of the PNS suggest that gas dynamics and star formation may well play an important role in the formation of the PNS observed in NGC 5128.

(6) The mass estimates of merger remnants viewed face-on are likely to be a factor of two lower than those viewed edge-on. However, even the mass estimates of systems viewed edge-on can be low by a factor of 5, and in the worst case (face-on E/S0 model) can be low by a factor of 5. If this conclusion is applicable to real early-type galaxies, it has interesting consequences for current observational work.
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APPENDIX A: DERIVATION OF 2D DENSITY AND VELOCITY FIELDS

In order to compare the simulated 2D density and velocity fields with the observed ones in a more self-consistent manner, we adopt the methods that are quite similar to those used for kinematical analysis of observational data of PNe in elliptical galaxies (e.g., PFF04a). We first determine the position angle ($\theta_p$) of the major axis of the stellar mass distribution projected onto the $x$-$z$ plane (i.e., perpendicular to orbital plane of galaxy merging) for each model at final time step. Then we rotate the model by $-\theta_p$ within the $x$-$z$ plane so that the major axis of the mass distribution can coincide with the $x$-axis. For convenience, the coordinate $(x, y, z)$ is renamed as $(X, Y, Z)$ after the rotation of the model. We represent the kinematics of a model by estimating line-of-sight (LOS) velocity moments as a function of position with a nonparametric smoothing algorithm. At the position of each stellar particle, we apply a local linear smoother using a Gaussian kernel function with the smoothing length of 0.17 in our units (corresponding to 3 kpc). We choose this value and secondly because we can more clearly see the detail of the 2D velocity field of a model throughout the outer halo region (extending to $R \sim 10R_e$). We divide the entire halo region with the size of $4R_d (= 70$ kpc corresponding to $\sim 14R_e$) into $50 \times 50$ cells for a merger model in each projection and estimate line-of-sight-velocity of $v(X_i, Z_i)$ for the $X - Z$ projection ($v(X_i, Y_i)$ and $v(Y_i, Z_i)$, for $(X_i, Y_i)$ and $(Y_i, Z_i)$, respectively), at the center of each cell, i.e., $(X_i, Z_i)$ ($i = 1 - 50$) based on the smoothed velocity filed (described above). Total number of cells in each projection is fixed at 2500 for all merger models in the present study, because we can more clearly see the global changes of 2D velocity field without suffering small-scale, and rapid variation resulting from small number of particles in each cell for this cell number. We mainly show the 2D velocity fields projected onto the $X$-$Y$ plane (referred to as the face-on view for convenience) and the $X$-$Z$ plane (the edge-on plane). The same method is used for estimation the 2D density field of the PNS in model.

In converting the 2D stellar mass density field into the 2D PNe one, we assume that the luminosity-specific PNe (number) density represented as $\alpha_{\text{PNe}} = 9.4 \times 10^{-9}$ PNe/$L_\odot$ (in $B$-band) This represents the number of PNe expected in the brightest 2.5 magnitudes of the PNLF, which is also roughly equivalent to the typical PN survey depth. Observations of M31's PNS (Ciardullo et al. 1989) showed that $\alpha_{\text{PNe}}$ can range from $2.9 \times 10^{-9}$ to $39.3 \times 10^{-9}$, and accordingly the adopted value above is consistent with these observations. This value of $9.4 \times 10^{-9}$, which originates from the 2nd column of the table 4 in Ciardullo et al. (1989), is used for $\alpha_{\text{PNe}}$ throughout this paper unless specified. While this is very obviously a simplification $- \alpha$ is known to vary as function of metallicity, and observational incompleteness will often vary across a galaxy—it is a good first-order approximation to the true PN population for our purposes. We also assume that $M/L_B = 3.5$ for stellar components of galaxies in all models.

The total number of PNe ($N_{\text{PNe}}$) within $5R_e$ of the simulated elliptical galaxies is typically $\sim 350$. As shown in Figure 1, even for the small number of star particles (1000) in the halo of the disk, the initial spherical distribution of PNe (stellar halo) can be reproduced reasonably well. In most of the merger models, typically 10% of the total stellar mass in the merger remnant can distribute throughout the halo regions ($R > 2R_e$). Therefore, more than $10^3$ stellar particles (up to $5 \times 10^5$) can be used to derive the smoothed density (velocity) field for a model. Thus we can derive the smoothly changing density (velocity) fields throughout the entire halo regions from original, more discrete density (velocity) ones for the adopted total number of stellar particles in simulations by using the smoothing method described above.

We also derive the radial profiles of rotational velocity ($V_{\text{rot}}$) and velocity dispersion ($\sigma$) for each model based on the same method as used for observational analysis on the NGC 5128 PNS (PFF04a). For example, when we try to derive the radial profile of $V_{\text{rot}}$ along the major axis of a PNS, we use PNe within either a perpendicular distance of $\pm 2$ kpc from the major axis or a $\pm 10^\circ$ cone centered on the major axis. This method is adopted so that more PNe can be included in the analysis of the radial profiles for the outer halo regions, where less number of stellar particles can prevent us from making a reasonable estimate of $V_{\text{rot}}$ and $\sigma$. The errors in $V_{\text{rot}}$ ($\sigma$) shown in figures of the present paper (e.g., Figure 7) are equal to $V_{\text{rot}}/\sqrt{2(N - 1)}$ ($\sigma/\sqrt{2(N - 1)}$, where $N$ is the total number of particles for a given radial bin. We do not intend to separately estimate $V_{\text{rot}}$ and $\sigma$ for PNe originating from spiral's stellar halos (thus metal-poor stars) and those from disks (metal-rich ones), partly because observational data sets on metallicities of PNe are not currently available. Although we find that there are no significant kinematical differences between metal-poor and metal-rich PNe in some models, we will discuss possible metallicity dependences of PNe kinematics in our forthcoming papers.

In order to investigate the smoothed 2D velocity fields, we use the same smoothing method as that used for deriving the 2D density fields of PNSs. The method of velocity smoothing is described as follows. The particle with the location $\mathbf{X}$, and the velocity $\mathbf{V}$, and the mass of $M$ is considered to be composed of $N_i$ particles (hereafter referred to as “smoothing particles”) that are located within $R$ (corresponding to smoothing length) from the particle (“parent particle”) and have position vectors of $\mathbf{x}_i$ ($i = 1 \sim N_i$) with respect to the parent, velocity vectors of $\mathbf{V}_i$ (i.e., the same as that of the parent), and masses of $M_{N_i}$. The spatial distribution of these smoothing particles with respect to the parent particle ($\mathbf{X}$) follows the Gaussian distributions. Therefore the probability of a $i$-th smoothing particle with the position of $\mathbf{X} + \mathbf{x}_i$ is proportional to $\exp(-r_i^2/2\sigma^2)$, where $r_i$ is the distance between the parent particle and the smoothing one. If the number of smoothing particles for a stellar particle is 100, the total number of “particles” used for 2500 bins is about $10^6$. Therefore, each bin includes 400 “particles” on average.

For each bin, we average the velocities of “particles” with the positions within the bin and derive the velocity at the location of the bin. The adopted smoothing length is consistent with that used for observations by PFF04a. Also we confirm that this method can reproduce the “spider shape” (which is characteristic of rotational kinematics) of the 2D velocity field of the initial disk. Thanks to this smoothing method, we can derive 2D density, velocity, and dispersion...
fields of PNSs that can be tested against the corresponding observations in a fully self-consistent manner.

This study is based totally on dissipationless simulations of galaxy mergers so that it can not discuss structure and kinematics of PNe formed from gas during/after galaxy merging. Accordingly, the present results can be more reasonably compared with the observed E/S0s formed from “dry” (dissipationless) mergers that do not create new PNe. In our future papers, we will discuss how the introduction of PNe formation in our numerical simulations can change main conclusions derived in the present study.

APPENDIX B: MULTIPLE MERGERS

Each multiple merger model contains equal-mass spiral galaxies with random orientations of intrinsic spin vectors which are uniformly distributed within a sphere of size $6R_d$. The most important parameter in this multiple merger model is the ratio of the initial kinematic energy ($T_{\text{kin}}$) of the merger to that of initial potential ($W$). By varying this ratio ($t_v$; defined as $|2T_{\text{kin}}/W|$) from 0.25 to 0.75, we investigate how $t_v$ controls the final PNe kinematics of the merger remnants. We mainly investigate the results of two extreme cases: (1) where the initial kinetic energy of a multiple merger is due entirely to the random motion of the five constituent galaxies (referred to as “dispersion supported”) and (2) where it is due entirely to (rigid) rotational motion (“rotation supported”). Our investigation of these two cases enables us to understand how the initial rotation (dispersion) can control the final kinematical properties of PNe in merger remnants.

Although we have derived the results of three models with $t_v = 0.25$, 0.5, and 0.75 for each case (i.e., six models in total), we describe the result of the “rotation supported” model with $t_v = 0.5$ (labeled as M10 in the Table 1). This is firstly because this multiple merger model show some interesting differences in PNe kinematics compared with pair merger models, and secondary because this model shows typical behaviors in PNe kinematics among multiple merger models. The merger remnant of this rotation supported model shows a flattened stellar (thus PNe) distribution if it is seen from edge-on and have effective radius of 11.4 kpc for the stars and 29.8 kpc for the dark matter halo.

We briefly summarize the results as follows. The radial gradient in $\sigma$ is significantly shallower in the multiple merger models than in pair merger models. These shallower $\sigma$ profiles in PNe kinematics can be seen in most multiple models and thus can be regarded as one of characteristics of PNSs in multiple merger remnants. The difference in $\sigma$ at each radial bin between PNe and dark matter halo is slightly larger than that seen in pair merger models Both dark matter halo and PNe show larger rotational velocities in the outer part of the halo and PNe can show larger $V_{\text{rot}}$ than dark matter halo.

Thus PNSs in elliptical galaxies formed by multiple mergers show similar kinematics to those in elliptical galaxies by pair mergers, though the maximum values of $\sigma$ and $V_{\text{rot}}$ can be different between the two cases owing to the larger masses in multiple mergers. Remarkable differences in PNe kinematics between the two different merger mod-