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Subaru Deep Imaging of Interacting Galaxies

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Abstract. We present deep optical images obtained with the Subaru Prime Focus Camera (Suprime-Cam) for nearby interacting galaxies. New tidal structures are revealed in many systems: remarkable examples include a northern faint extension of the Antennae, a large extension of Arp 220 – doubling the size from the previously-known, and a new tidal tail of Mrk 231. These extended features constrain the orientations and orbits of progenitor galaxies; the large extensions indicate that their rotations were retrograde with respect to the orbits. The orientations of the progenitors may constrain the timescale that merging completes, the duration of gravitational perturbation, and the timescale of gas fueling to galactic centers. This introduces an additional parameter (i.e. orientation of spin) in categorizing the evolutionary sequence of merging based on optical images.

1. Suprime-Cam Deep Imaging

Subaru observations happened as a back-up program of the Subaru-COSMOS project (Taniguchi et al. 2006). The telescope had a tracking problem at the night –a pointing jumped in a random direction roughly every 1 minute exposure and instantly came back to the designated pointing position. These jumps produced artificial traces around bright stars, with a typical length of $8''$ and amplitude of $\sim 1\%$ peak intensity of a star. This is a serious problem for the COSMOS measurements, but is negligible in detecting faint extended structures ($\gg 8''$). In particular, the search for large tidal tails of interacting galaxies require a wide field-of-view on a large telescope; the Subaru prime focus camera (Suprime-Cam; Miyazaki et al. 2002) on board at the night is the best for this purpose. Its large field-of-view, $\sim 34' \times 27'$, covers even the largest interacting system, the Antennae $\sim 20'$, in a single shot. Thus, we started searching unknown faint tidal tails around interacting galaxies, and observed 13 systems by the end of the night. The pointing jumps are sometimes evident even in reduced images, but clearly do not cause any problem in the discussions in this contribution. All the systems were observed at R_C-band, and two of them were observed at B_J-band as well. We reduced the data with the software developed and provided by Masafumi Yagi (Yagi et al. 2002).

2. Faint Tidal Tails of Interacting Galaxies

2.1. The Antennae

A new tidal component is discovered at the tip of the north tidal tail, forming an "arrow" shape toward the north (Figure 1). It appears to be detached from the main tail in the sky projection. The projected extension is $\sim 5'$ in the east-west direction, i.e. 38 kpc assuming the commonly-adopted distance of 26 Mpc.

Its total apparent magnitude is ~ 14.6 mag in R-band, and the absolute luminosity is $\sim 5\times10^8 \mathrm{L}_\odot$ with a large error due to the contamination of foreground and background objects. The surface brightness over this component is smooth and low, and is typically $\sim 26.0\,\mathrm{mag\,arcsec^{-2}}$ in R-band and $\sim 27.1\,\mathrm{mag\,arcsec^{-2}}$ in B-band. No distinct internal structure is found within this component. A similar tidal component has been known at the tip of the southern tidal tail (Mirabel, Dottori & Lutz 1992), and its apparent magnitudes, 14.4 mag in R-band and 15.3 mag in B, are also similar to those of the northern component. The southern component is often discussed as a self-gravitating structure, or tidal dwarf galaxy (Mirabel, Dottori & Lutz 1992), however, the northern component is unlikely a gravitationally-bound nor collapsing structure, because of the low surface density. Extinction is presumably negligible, since distant galaxies in the background field are seen through this component, and their surface number density is similar to those in other parts of sky. HI gas is not associated entirely to this component, although some HI 21 cm emission is detected at its western end (see Hibbard et al. 2001). The color, $B-R=+0.9$, is close to those of F and G-type stars, indicating a mature stellar composition. No significant color change is found between this component and the main tidal tail; therefore, the stars in this component likely belonged to a progenitor galaxy and escaped as the main tail.

The two main tidal tails are remarkably broad. The northern tail has a $\sim 2'$ width (15 kpc), while the southern tail shows typically $\sim 3'$ width (22 kpc) in sky projection. The surface brightness at their outskirts reaches as faint as $\sim 26.1\mathrm{mag\,arcsec^{-2}}$ in the R-band image. The wide optical tails overlap with the gas tails that are traced in HI emission (Hibbard et al. 2001), presumably indicating that both gas and stars are ejected from similar regions in progenitor galaxies.

2.2. Arp 220

Ohyama et al. (1999) found a large tidal tail of Arp 220 that runs toward the south. The Subaru image (Figure 2) reveals its whole extension, about twice a larger area ($\sim 1.5'$ larger extension; 33 kpc) than the widely known (i.e. only the bright central $\sim 2'$; Kim 2002). The surface brightness does not vary much across this component, and is about 25.8 $\mathrm{mag\,arcsec^{-2}}$ in R-band. Along the southern edge of this component, there is a ridge that is slightly brighter than the rest (about $-0.3\,\mathrm{mag\,arcsec^{-2}}$) and presumably a new tidal tail.

Two smaller galaxies apparently overlap on the south-west tip of the tail, but their redshifts ($z=0.089$ and 0.091; Ohyama et al. 1999; Koulouridis et al. 2006) are significantly different from that of Arp 220 ($z=0.018$). Another galaxy at the east side is also at a higher redshift ($z=0.037$; Koulouridis et al. 2006). Therefore, they are not associated with the southern tidal tail.

The traces of the unstable telescope pointing are apparent around bright stars. They extend toward east from the stars with the length $\sim 14''$ and flux of about 1% of the peak flux. These artifacts are much smaller than the extension of the new tidal component, and thus, are negligible in our discussion.

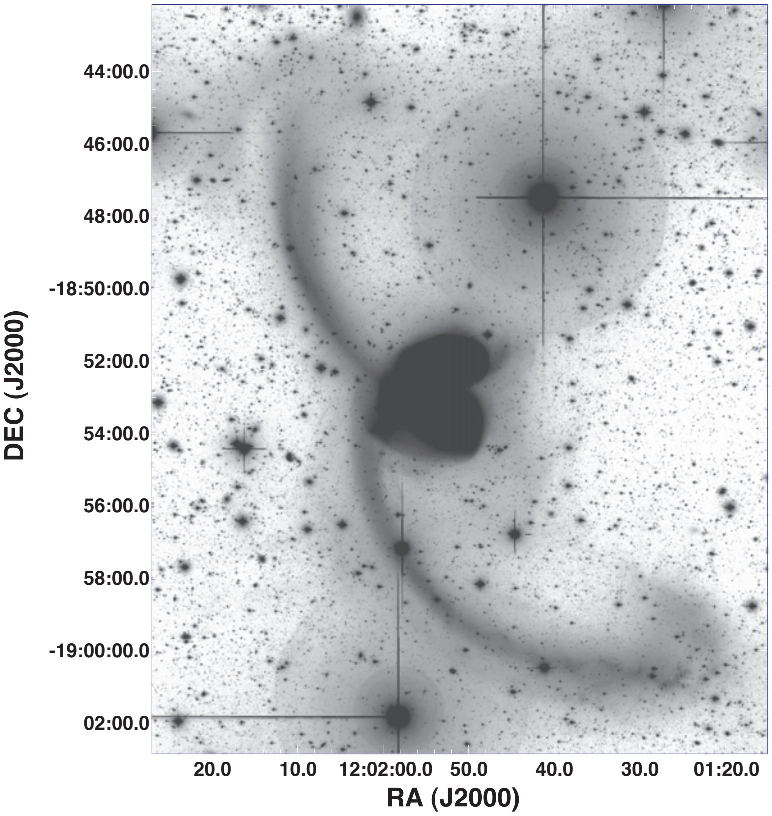

Figure 1. Subaru/Suprime-Cam R_{C}-band image of the Antennae.

2.3. Mrk 231

The Subaru image clearly reveals a tidal tail at the east side of the main galaxies (Figure 3). The presence of this component has been known in previous optical studies (e.g. Canalizo & Stockton 2000), however, its whole extension, $\sim 1.5'$ (78 kpc), is uncovered for the first time. Its surface brightness is $\sim 24.5\,\mathrm{mag\,arcsec^{-2}}$. There is a ridge along its southern edge, which is slightly brighter than the rest of the area and possibly a tidal tail with $\mu_{\mathrm{R}} \sim 25.0\,\mathrm{mag\,arcsec^{-2}}$.

Two main tails run toward the north and south from the main galaxies, and have been obvious even in previous images. In comparison with these two tails, the new tidal component is much fainter and more extended. From its large extension, the new component is probably the eject at the first encounter viewed nearly face-on.

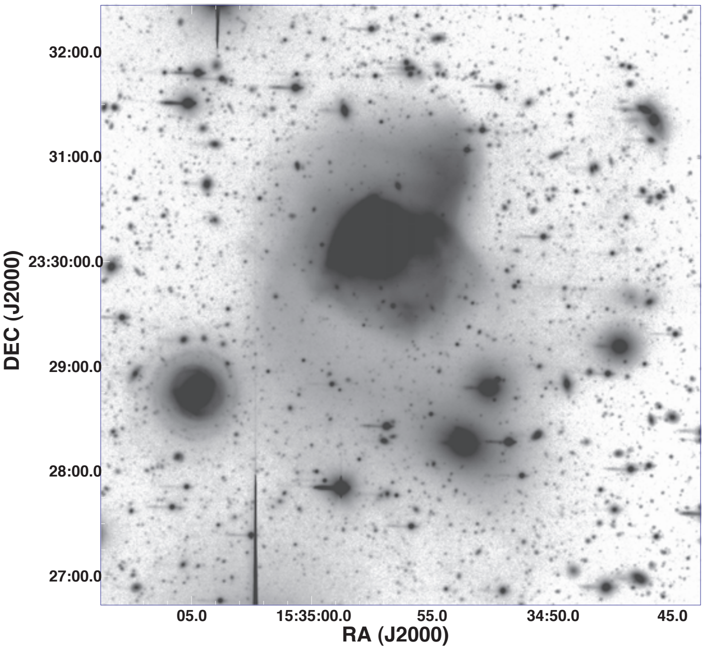

Figure 2. Same as Figure 1, but for Arp 220.

3. Discussion

3.1. Formation of Tidal Tails

New tidal tails constrain the orientations and orbits of progenitor galaxies. In particular, the presence of one substantial tidal tail indicates that one of progenitors' spins is prograde with respect to their orbital motion (see Toomre & Toomre 1972). An encounter of two galaxies with prograde-spins leads to two tidal tails (e.g. the Antennae). To understand this, we calculate the condition for the formation of a tidal tail in term of spin direction in a simple case, i.e. in-plane passage. We consider a test particle, *star*, that rotates around the progenitor galaxy A, and evaluate the tidal force and duration of encounter that are necessary for the star to escape from A's gravitational potential and to form a tidal tail.

How much energy/velocity does the star need to gain to escape from the gravitational potential? A large tidal tail, by definition, extends away from the potential well of a progenitor galaxy. The stars in the tail, therefore, should have a velocity similar to the escape velocity from the galaxy, i.e. $V_{\rm esc} \sim \sqrt{2} V_{\rm rot}$. If we adopt a typical rotation velocity of a galaxy $V_{\rm rot} \sim 200\,{\rm km\,s^{-1}}$, the velocity gain that is necessary for the star to escape is $dV = V_{\rm esc} - V_{\rm rot} \sim 100 {\rm km\,s^{-1}}$.

How long does it take the star to obtain dV by tidal interaction? Tidal acceleration $a_{\rm tidal}$ depends strongly on the position of the star with respect to those of the galaxies A & B. It becomes the maximum when the star lies on the

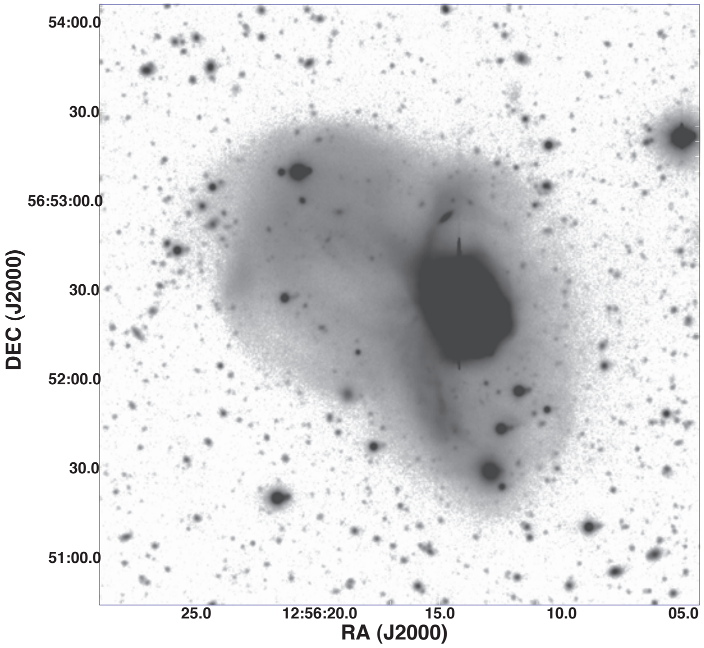

Figure 3. Same as Figure 1, but for Mrk 231.

line of the two galaxies' centers, but is zero when it is on the line perpendicular to it. Here we assume that the pericenter separation of the encounter is twice larger than the diameter of the galaxy A, and adopt the galactic mass $M = 4\times10^{11}\,\mathrm{M}_\odot$, diameter $D = 20\,\mathrm{kpc}$, and the pericenter separation $R = 40\,\mathrm{kpc}$. The maximum tidal acceleration is $a^{\max}_{\rm tidal} = 2GMD/R^3 \sim 4\times10^{-9}\,\mathrm{cm\,s^{-2}}$. We note again that the tidal force varies from 0 to $a^{\max}_{\rm tidal}$, depending on the configuration. *Even with the maximum tidal force, it takes the star* $dV/a^{\max}_{\rm tidal} \sim 10^8\,\mathrm{yrs}$ *to obtain an enough energy/velocity to escape from its host galaxy due to the tidal interaction.*

This is a significant fraction of the orbital timescale of the encounter, i.e. a few $\times10^8$ yrs. A prograde star receives the maximum force for the duration of encounter, since it follows the other galaxy around its orbit. The new large tidal tails, therefore, suggest that the progenitor galaxies had prograde spins with respect to the orbits of encounter. We found large tidal tails in Arp 220 and Mrk 231, indicating that one of their progenitor galaxies had a prograde spin with respect to the orbital motion. Sakamoto et al. (1999) suggested that the two cores or Arp 220 are counter-rotating to each other, which is consistent with this view – an encounter of prograde and retrograde spins with respect to the orbital motion.

3.2. Timescale of Orbital Decay and Central Activities

The orientation of galactic disk may affect the timescale of orbital decay, and the duration of central activities. Galaxies lose their orbital energies and merge by converting them into the internal motions of galaxies due to dynamical friction. The force of dynamical friction is proportional to $1/V_{\rm rel}^2$, where $V_{\rm rel}$ is the relative velocity, e.g. between the sinking galaxy B and the internal medium of the galaxy A (i.e. stars and dark matter). The energy conversion is more efficient and the merging completes more rapidly when $V_{\rm rel}$ is low.

The orbit would decay more rapidly when the orbital motion of B is coupled with the rotation of A's disk. That is, if A has a prograde spin with respect to the orbit, B merges into A's disk in its rotation direction. The relative velocity between B and A's disk is then $V_{\rm rel} \sim V_{\rm rot} - V_{\rm orb}$ in the case of in-plane encounter, where $V_{\rm rot}$ is the rotation velocity of A and $V_{\rm orb}$ is the orbital velocity of B. In contrast, it becomes $V_{\rm rel} \sim V_{\rm rot} + V_{\rm orb}$ in the case of a prograde spin. The galaxy B is trapped in A's gravitational potential, and $V_{\rm orb}$ is close to $V_{\rm rot}$; therefore, $V_{\rm rel}$ is small in the prograde case. The dynamical friction due to stellar disk is potentially very efficient in prograde merging. This effect has been observed in numerical simulations (e.g. Farouki & Shapiro 1982; Barnes 1992).

Gas fueling to galactic centers may last longer (shorter) in retrograde (prograde) case; since perturbations persist until two galaxies merge completely. We discussed only the cases of in-plane encounters, and the dynamical friction due to dark matter becomes more important in off-plane encounters. Large tidal tails, however, form preferentially in in-plane cases (Toomre & Toomre 1972). The discovery of the new tidal tails may suggest that a progenitor of these systems had a prograde spin, possibly indicating that their central activities last relatively short.

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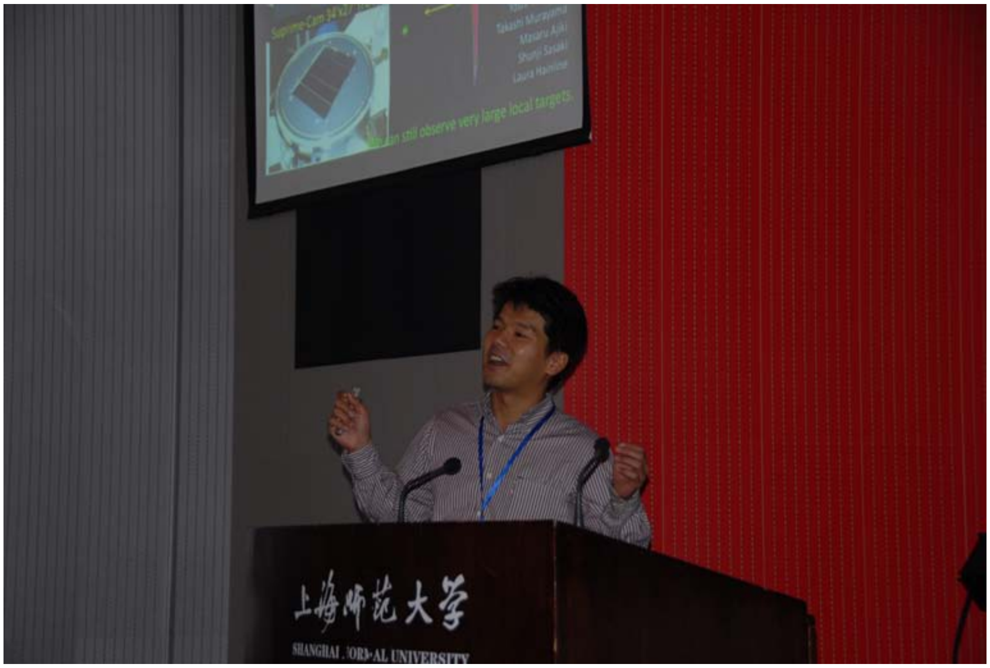

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