Sumo Puff: Tidal Debris or Disturbed Ultra-Diffuse Galaxy?

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Abstract

We report the discovery of a diffuse stellar cloud with an angular extent $\gtrsim 30''$, which we term "Sumo Puff", in data from the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP). While we do not have a redshift for this object, it is in close angular proximity to a post-merger galaxy at redshift $z = 0.0431$ and is projected within a few virial radii (assuming similar redshifts) of two other $\sim L_\star$ galaxies, which we use to bracket a potential redshift range of $0.0055 < z < 0.0431$. The object's light distribution is flat, as characterized by a low Sérsic index ($n \sim 0.3$). It has a low central g-band surface brightness of ~ 26.4 mag arcsec^{-2}, large effective radius of $\sim 13''$ (~ 11 kpc at $z = 0.0431$ and ~ 1.5 kpc at $z = 0.0055$), and an elongated morphology ($b/a \sim 0.4$). Its red color ($g - i \sim 1$) is consistent with a passively evolving stellar population and similar to the nearby post-merger galaxy, and we may see tidal material connecting Sumo Puff with this galaxy. We offer two possible interpretations for the nature of this object: (1) it is an extreme, galaxy-size tidal feature associated with a recent merger event, or (2) it is a foreground dwarf galaxy with properties consistent with a quenched, disturbed ultra-diffuse galaxy. We present a qualitative comparison with simulations that demonstrates the feasibility of forming a structure similar to this object in a merger event. Follow-up spectroscopy and/or deeper imaging to confirm the presence of the bridge of tidal material will be necessary to reveal the true nature of this object.

Key words: keywords

1 Introduction

Ongoing surveys are now revealing the low-surface-brightness universe as never before. Breakthroughs with observing strategies and data reduction (e.g., Dalcanton et al. 1997a; Blanton et al. 2011; Ferrarese et al. 2012; Duc et al. 2015; Fliri & Trujillo 2016; Trujillo & Fliri 2016) and small robotic telescopes (Abraham & van Dokkum 2014; Javanmardi et al. 2016) have allowed us to explore diffuse structures with surface brightnesses $\mu > 25$ mag arcsec^{-2} routinely, providing new insights into the full galaxy population (Disney 1976), the halos of massive galaxies (Merritt et al. 2016a; Mihos et al. 2017; Huang et al. in prep.), and the hierarchical build-up of galaxies (van Dokkum 2005; Tal et al. 2009). Our ongoing Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP; Aihara et al. 2017b), which recently had its first public data release (Aihara et al. 2017a), is imaging the sky with an unprecedented combination of depth and area ($i \sim 26$ AB mag over 1400 deg^2 upon completion). This data set will have enormous potential to reveal populations of low-surface-brightness phenomena across a diverse range of environments, opening a new window into the ultra-diffuse universe.

Fainter surface brightness limits invariably result in the discovery of new galaxies. This fact was recently demonstrated with the discovery of $\sim$1000 so-called ultra-diffuse galaxies in the Coma cluster (van Dokkum et al. 2015; Koda et al. 2015), which are characterized by central surface brightnesses $\mu_0(g) > 24$ mag arcsec^{-2} and effective radii $r_{\rm eff} > 1.5$ kpc. Although the existence of such faint and extended galaxies has been known for decades (e.g., Sandage & Binggeli 1984; Impey et al. 1988; Bothun et al. 1991; Dalcanton et al. 1997a; McConnachie et al. 2008), such an abundant cluster population was not expected, and this has renewed interest in studying galaxies in the ultra-low-surface-brightness regime. Large-scale, systematic observations optimized at low surface brightnesses will be necessary to uncover the nature of ultra-diffuse galaxies; for example, their number density as a function of environment may reveal what fraction are "failed" $L_\star$ galaxies (van Dokkum et al. 2015), with massive ($\sim 10^{12}$ $M_\odot$) dark matter halos like Dragonfly 44 (van Dokkum et al. 2016), versus what fraction represent the high-spin tail of the dwarf galaxy population (Dalcanton et al. 1997b; Amorisco & Loeb 2016). Another interesting possibility is that some ultra-diffuse galaxies are "normal" dwarf galaxies that are being disrupted by more massive hosts (Crnojević et al. 2016; Toloba et al. 2016; Merritt et al. 2016b), similar to dwarf spheroidal galaxies in the Local Group (Collins et al. 2013).

In the ΛCDM cosmological framework, low-surface-brightness substructure and tidal debris are also the inevitable detritus of the hierarchical build-up of stellar halos. At surface brightnesses fainter than $\sim$27–30 mag arcsec^{-2}, massive galaxies are predicted to be engulfed in a rich network of tidal streams, shells, and tails (Bullock & Johnston 2005; Johnston et al. 2008; Cooper et al. 2010). Low-surface-brightness observations have confirmed this expectation around nearby elliptical galaxies (van Dokkum 2005; Tal et al. 2009; Duc et al. 2015), spiral galaxies in the local volume (Martínez-Delgado et al. 2010), and the high-density cluster environment (Mihos et al. 2017). Such observations contain a wealth of information about the accretion history of massive galaxies. In addition, large samples of the low-surface-brightness substructure and tidal features around nearby galaxies (e.g., Atkinson et al. 2013) have the potential to constrain the orbital parameter distributions of merging satellites, which would have important implications for the formation of structure in the universe (Hendel & Johnston 2015).

As we push to unbiased wide area surveys, such as HSC-SSP, natural confusion arises between these two sources of low-surface-brightness material (diffuse galaxies and tidal debris). Namely, they sometimes have very similar photometric properties and, when data are limited, can be indistinguishable from one another. While tidal debris is in general clearly connected to a primary system by low-surface-brightness streams and tails, tidal interactions are also capable of producing relatively isolated, giant stellar clouds (e.g., Johnston et al. 2008; Martínez-Delgado et al. 2010). Diffuse-galaxy searches will detect such features as individual galaxies when in fact they are the debris of galaxy interactions.

In this paper, we report the discovery of an object that falls into this ambiguous category. The object was discovered as part of our ongoing hunt for ultra-diffuse galaxies in data from the HSC-SSP. In Section 2, we discuss the data and identification of the object. We present the object's structural, photometric, and environmental properties in Section 3. In Section 4, we present two possible interpretations of the nature of the object, and we conclude with discussion in Section 5. Throughout this work, we assume standard ΛCDM cosmological parameters: $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}.

2 Data and Identification

The data were taken with the Hyper Suprime-Cam (HSC; Miyazaki et al. 2012) on the 8.2-meter Subaru Telescope as part of the wide layer of the HSC-SSP, an ambitious 300-night, wide-field multi-filter imaging survey (Aihara et al. 2017b). Utilizing HSC's large field of view (1.5 deg in diameter) and the large telescope aperture, this survey will achieve $i \sim 26$ AB mag (5σ point-source depth) over 1400 deg^2 upon completion. Standard data reductions were performed using *hscPipe*, a modified version of the Large Synoptic Survey Telescope (LSST) software stack (Ivezic et al. 2008; Axelrod et al. 2010; Jurić et al. 2015). For details about *hscPipe* and the HSC-SSP data reductions, see Bosch et al. (in prep.) and Aihara et al. (2017a).
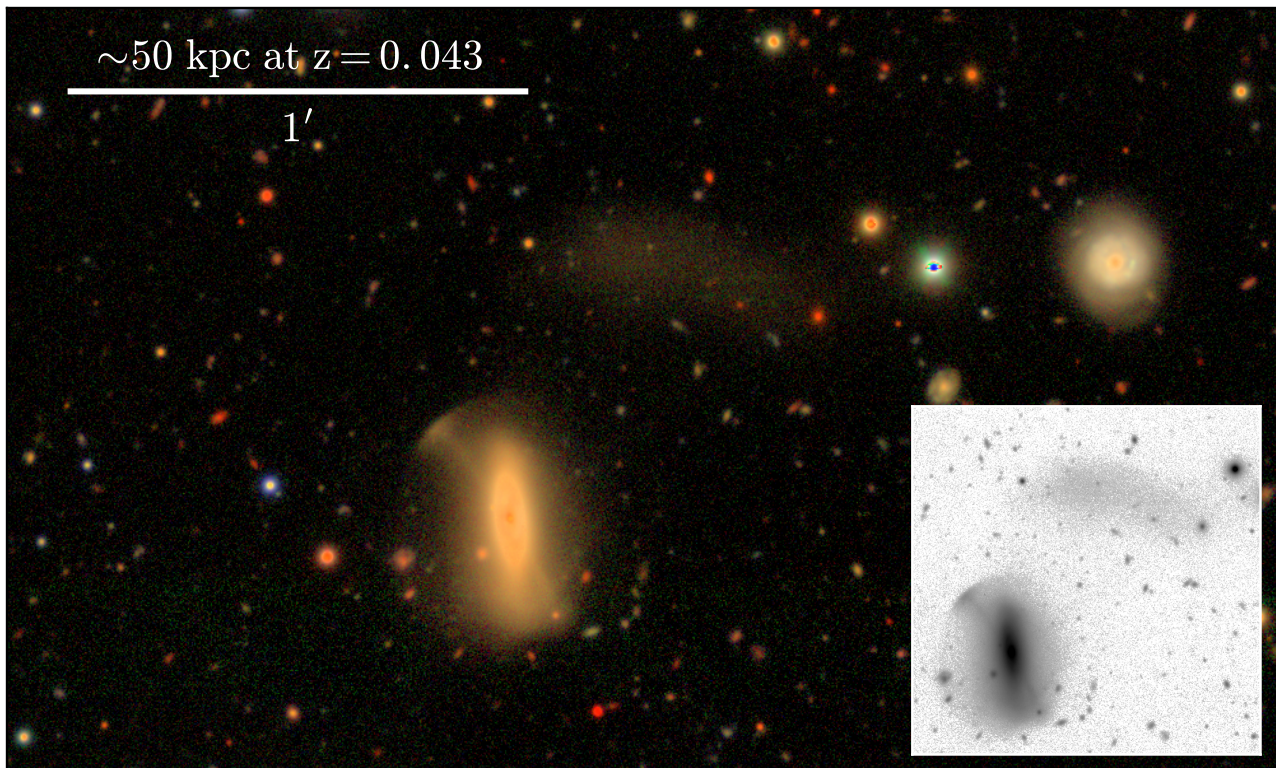
Fig. 1. HSC-SSP gri-composite image (Lupton et al. 2004) of Sumo Puff and the post-merger galaxy SDSS J1449-0042. The inset shows the i-band image with a logarithmic stretch. Note the very sharp caustic feature associated with SDSS J1449-0042, which is due to a turnaround point in stellar orbits that manifests as a caustic in surface brightness. If Sumo Puff is at the redshift of SDSS J1449-0042 (z=0.0431), then it is > 26 kpc in diameter. North is up, and east is to the left.

Taking advantage of the unprecedented combination of depth and wide-area coverage afforded by HSC-SSP, we are using this data set to carry out a systematic search for ultra-diffuse galaxies outside of cluster environments (Greco et al. in prep.). Currently, *hscPipe* is not optimized to find low-surface-brightness objects. With central surface brightnesses $\sim$3–5 magnitudes fainter than the night sky, the light from such sources is easily dominated by background/foreground objects. As a result, the *hscPipe* photometric deblender shreds them into many smaller constituent parts, a problem that is well known to exist in the Sloan Digital Sky Survey (SDSS; York et al. 2000) but is much more pronounced at the depth of HSC-SSP. Therefore, we are developing custom tools based on the LSST software stack to perform our diffuse-galaxy search.

During the development of our software, we discovered a giant stellar cloud, "Sumo Puff", whose origin and physical nature is currently ambiguous. In Figure 1, we show its gri-composite image. This source was selected by our automated pipeline due to its large angular size and low "central" surface brightness. The details of our pipeline will be given in a paper devoted to our primary search.

We note that Sumo Puff is clearly visible in all five bands covered by HSC-SSP ($grizy$) and is detected in individual ex-

posures, which are taken at a range of dither positions. For g and r, every point within the wide layer footprint is observed with 4 exposures per band arranged on a hexagonal grid with the boresight offset by $36'$; for izy, a similar pattern is used except with 6 exposures per band (see Aihara et al. (2017b) for details of HSC-SSP's observing strategy). Thus, we are confident that Sumo Puff is a real astrophysical source as opposed to an optical artifact such as a ghost or scattered light from a bright star.

At the depths of HSC-SSP, optical scattered light from galactic cirrus can mimic unresolved stellar systems (e.g., Duc et al. 2015; Miville-Deschênes et al. 2016). While the structure of Sumo Puff appears qualitatively different from the wispy structure characteristic of galactic cirrus, it is nevertheless important to rule out this possibility. If Sumo Puff is a Milky Way cirrus cloud, then it will likely have a mid/far-infrared counterpart with thermal dust emission. We searched for such a counterpart in the galactic dust map of Meisner & Finkbeiner (2014), which is based on a reprocessing of the Wide-field Infrared Survey Explorer 12 μm imaging data set. We find no potential infrared counterpart. The region of sky $\sim$2° around Sumo Puff has relatively little 12 μm emission. At Sumo Puff's location, there are no visible structures, and the 12 μm signal is well within 1σ of
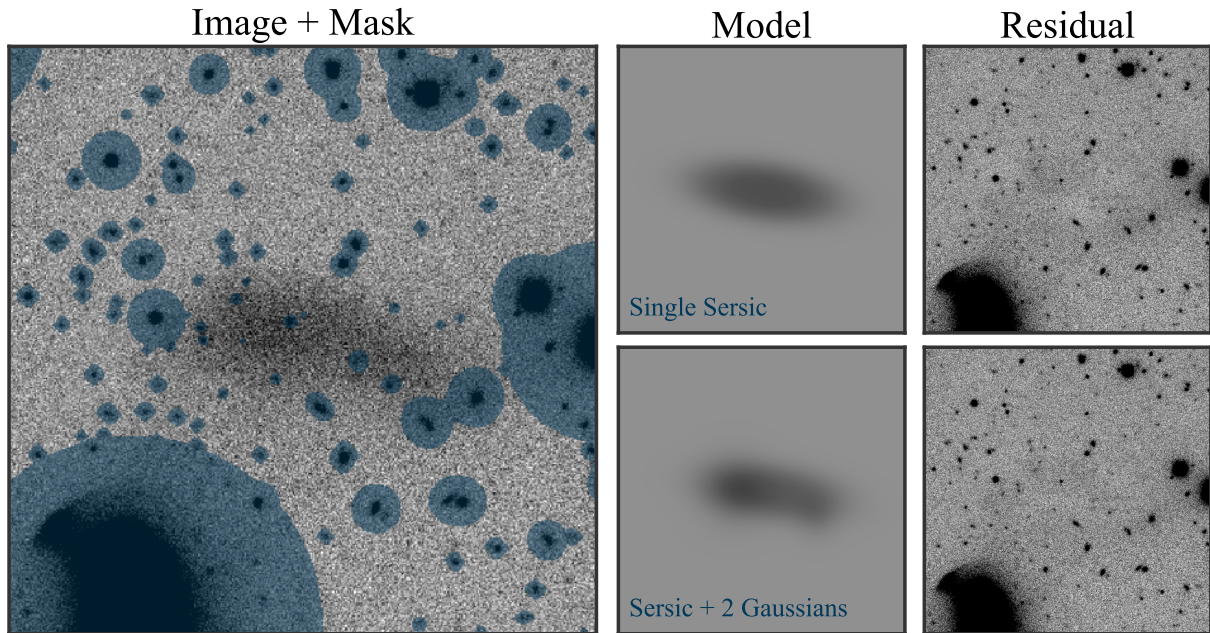
Fig. 2. *Left:* The r-band image with an overlay of the object mask. We use the same mask for all bands. *Right:* The best-fit single-component (top row) and three-component (bottom row) models and the associated residuals. We summarize the model parameters in Table 1. The g- and i-band fits produce qualitatively similar results. The dimensions of each cutout are $\sim 70'' \times 70''$.

the background level.

3 Observed Properties of Sumo Puff

In HSC-SSP images, Sumo Puff appears as a diffuse cloud with unresolved stellar populations, an enormous apparent size ($\gtrsim 30''$ in diameter), and an elongated, peanut-like morphology (see Figure 1). Furthermore, it is in close angular proximity to a visually striking post-merger galaxy (SDSS J144916.46-004240.5; SDSS J1449-0042 hereafter) with a similar red color, which hosts a massive tidal stream with a sharp turnaround point in stellar orbits that manifests as a caustic in surface brightness (Tremaine 1999). It is tempting to assume that Sumo Puff is tidal debris associated with SDSS J1449-0042. In this work, we consider this possibility along with the alternative hypothesis that it is a foreground dwarf galaxy with properties that are consistent with a disturbed ultra-diffuse galaxy.

3.1 Structure and Photometry

To characterize the structural and photometric properties of Sumo Puff, we run *imfit*[1] (Erwin 2015) on the sky-subtracted g-, r-, and i-band images. When performing the fit, we use the noise images, object masks, and point-spread function (PSF) measurements generated by the standard HSC-SSP photometric pipeline. We mask additional objects by hand, which fall within the source footprint and are not covered by the HSC-SSP

[1] http://www.mpe.mpg.de/~erwin/code/imfit/

Parameter	Value
α_{2000}	$222.31310°$
δ_{2000}	$-0.70188094°$
$r_{\rm eff}$	$13.2''$
Sérsic n	0.32
b/a	0.38
m_g	20.0
$g - i$	1.0
$g - r$	0.68
$\mu_0(g)$	26.4 mag arcsec^{-2}
$\mu_{\rm eff}(g)$	26.8 mag arcsec^{-2}

Table 1. Sumo Puff properties. Photometric and structural properties assume a single-component Sérsic model. The total magnitudes from our independent multi-component fits are within ~ 0.02 mag of those presented in this table.

object masks. For simplicity, we model the surface brightness distribution as a two-dimensional, PSF-convolved Sérsic function (Sersic 1968). We first fit each band separately, allowing all parameters to vary; the resulting shape parameters differed by only a few percent across the bands. We adopt their mean values, which are summarized in Table 1. To measure the color, we perform the fits again on each band with the shape parameters fixed to their mean values, allowing only the amplitude to vary. We find the light distribution to be very flat, characterized by a low Sérsic index ($n \sim 0.3$). However, it is not smooth on large scales. The residual image indicates a lumpy morphology
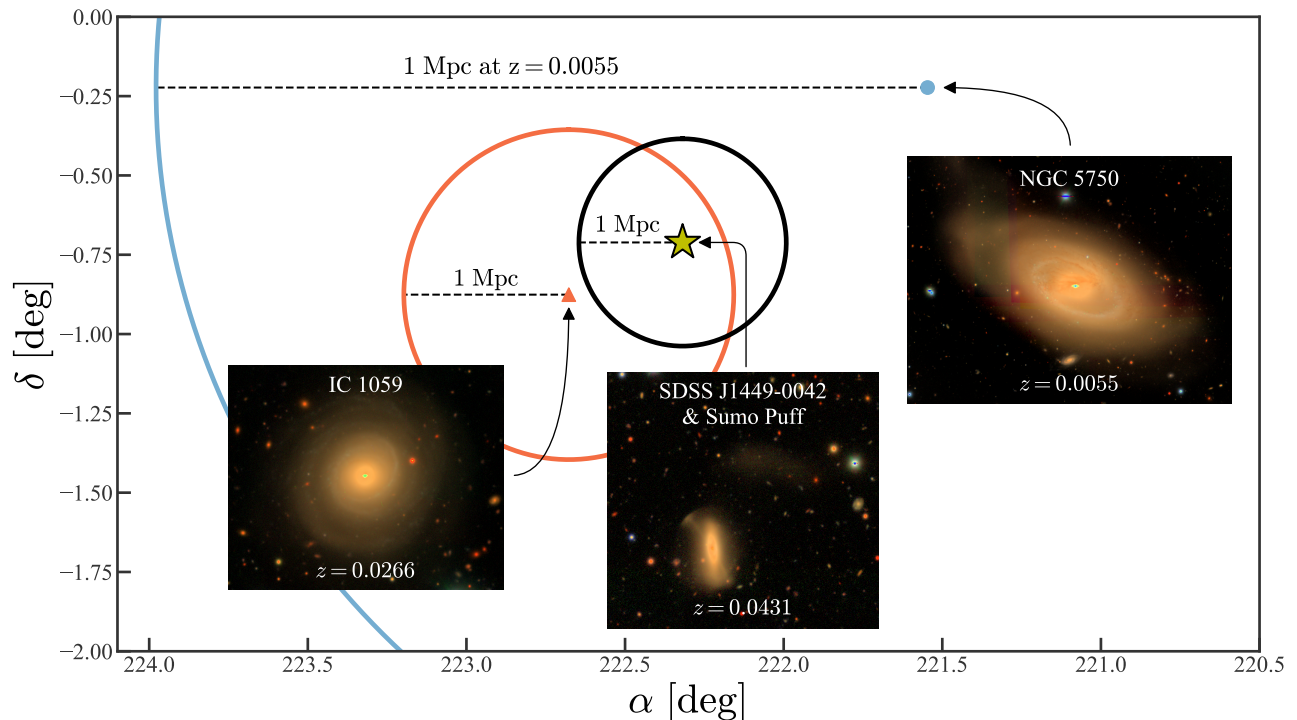
Fig. 3. Positions of Sumo Puff and three potential host galaxies, which are each the nearest $\sim L_\star$ galaxy to Sumo Puff (assuming similar redshifts) in the redshift ranges we selected from the NSA galaxy catalog (see Section 3.2 for details). For reference, we also show HSC cutout gri-composite images of each host candidate and circles representing their associated 1 Mpc search region. This search radius corresponds to $\sim$3–4 virial radii for the Milky Way and encompasses the region within which we expect to find quenched dwarf galaxy satellites around massive hosts. Due to NGC 5750's very low redshift, its circle extends beyond the limits of the figure. Note that the relative sizes of the cutout images are not to scale.

that is not well-captured by a single-component fit.

Therefore, we also measure the total flux using a three-component model composed of a Sérsic function and two elliptical Gaussians. In each band, we convolve this multi-component model with the PSF before comparing with the imaging data. In Figure 2, we show the r-band image with an overlay of the object mask, the best-fit single- and multi-component models, and the associated residuals. The g- and i-band fits show qualitatively similar results. The total magnitudes of the single- and multi-component models are consistent at the $\sim$0.02 mag level. We adopt the single-component Sérsic model parameters, which are summarized in Table 1.

3.2 Environment

Given Sumo Puff's morphology and apparent proximity to the post-merger SDSS J1449-0042, it is tempting to associate the two objects; however, an equally viable possibility given the available data is that it is a foreground dwarf galaxy, whose alignment with SDSS J1449-0042 is the result of chance. Assuming Sumo Puff is a foreground dwarf galaxy, its red color—which is consistent with a passively evolving stellar population—suggests it has at least one luminous companion; quenched dwarf galaxies are rarely ($< 0.06\%$) found in isola-

tion, almost exclusively being within 2 virial radii of a massive galaxy (Geha et al. 2012). Thus, we bracket a potential distance range to Sumo Puff using the redshifts of its nearest neighbors on the sky.

We carry out a search for potential massive hosts using the NASA-Sloan Atlas[2] (NSA), which includes virtually all galaxies with known redshifts out to $z < 0.055$ within the coverage of SDSS DR8 (Aihara et al. 2011). We consider galaxies with redshifts $0.002 < z < 0.055$ and stellar masses $\log_{10}(M_\star/M_\odot) > 10$. The low-$z$ cut removes optical artifacts, bright stars, and galaxies with negative redshifts; and the high-z cut is set by the NSA catalog and extends beyond the redshift of the post-merger galaxy SDSS J1449-0042 ($z = 0.0431$) seen in Figure 1. The stellar masses in the NSA are calculated using *kcorrect* (Blanton & Roweis 2007), which assumes the initial mass function of Chabrier (2003). We then select any galaxy with a co-moving separation less than 1 Mpc from Sumo Puff *assuming* that they are at the same redshift. For the Milky Way, this separation corresponds to $\sim$3–4 virial radii (Bland-Hawthorn & Gerhard 2016, and references therein), which encompasses the region within which the vast majority of quenched dwarf galaxies are expected to reside near a massive host (Geha et al. 2012).

[2] http://nsatlas.org

The above search produces 7 galaxies that fall roughly into 3 redshift bins: $z \sim 0.006$, 0.03, and 0.04. Of these 7 galaxies, we select the nearest to Sumo Puff (assuming similar redshifts) in each redshift bin as potential hosts, yielding 3 host galaxy candidates. In Figure 3, we show the position of Sumo Puff along with the potential hosts, all of which have stellar masses comparable to $L_\star$ galaxies. For reference, we also show HSC cutout images of each host candidate and circles representing their associated 1 Mpc search region. Without knowing Sumo Puff's distance, it is possible that it is a member of any of these systems. The lowest redshift host candidate is NGC 5750 at $z = 0.0055$, and the highest redshift host candidate is the post-merger SDSS J1449-0042 at $z = 0.0431$. We, therefore, assume Sumo Puff's potential redshift range to be $0.0055 < z < 0.0431$.

If Sumo Puff is in fact tidal debris associated with SDSS J1449-0042, then it is at $z = 0.0431$. On the other hand, if it is a satellite dwarf galaxy, then it may be at any redshift in the above range, with three potential host galaxies shown in Figure 3 — even at the smallest possible distance in the assumed range (~ 24 Mpc), Sumo Puff's physical properties would be consistent with a disturbed ultra-diffuse galaxy. We consider each of these scenarios below.

4 What is Sumo Puff?

4.1 Tidal debris associated with SDSS J1449-0042

In this scenario, Sumo Puff is not actually a galaxy at all. Rather, it is tidal debris associated with the recent merger that is apparent in SDSS J1449-0042 at $z = 0.0431$. It has a dramatic effective radius of $r_{\rm eff} \sim 11$ kpc and an i-band absolute magnitude of $M_i \sim -17.4$ mag. Using the mass-to-light ratio/color relation derived from Bell et al. (2003), this corresponds to $\sim 1.3 \times 10^9$ $M_\odot$ of stars. At this redshift, Sumo Puff is projected within ~ 20–30 kpc from the center of SDSS J1449-0042 — well within its virial radius. If true, this scenario naturally explains Sumo Puff's lumpy and elongated ($b/a \sim 0.4$) morphology, red color ($g - i \sim 1$), and close proximity to SDSS J1449-0042.

It is interesting to speculate on the possible geometry leading to this very extended yet remote tidal feature, which appears to lack any sharp edges in its surface brightness profile. Qualitatively similar giant stellar clouds have been observed in the diffuse stellar halos of nearby spiral galaxies (Martínez-Delgado et al. 2010; Martínez-Delgado et al. 2012), the tidal streams of dwarf galaxies (Rich et al. 2012; Martínez-Delgado et al. 2015), and in simulations of the formation of stellar halos around Milky-Way-type galaxies (Bullock & Johnston 2005; Johnston et al. 2008). For example, the left panel of Figure 17 of Johnston et al. (2008) shows a large plume with some resemblance to Sumo Puff; the authors attribute such features to the accretion of a satellite on a radial orbit. However,
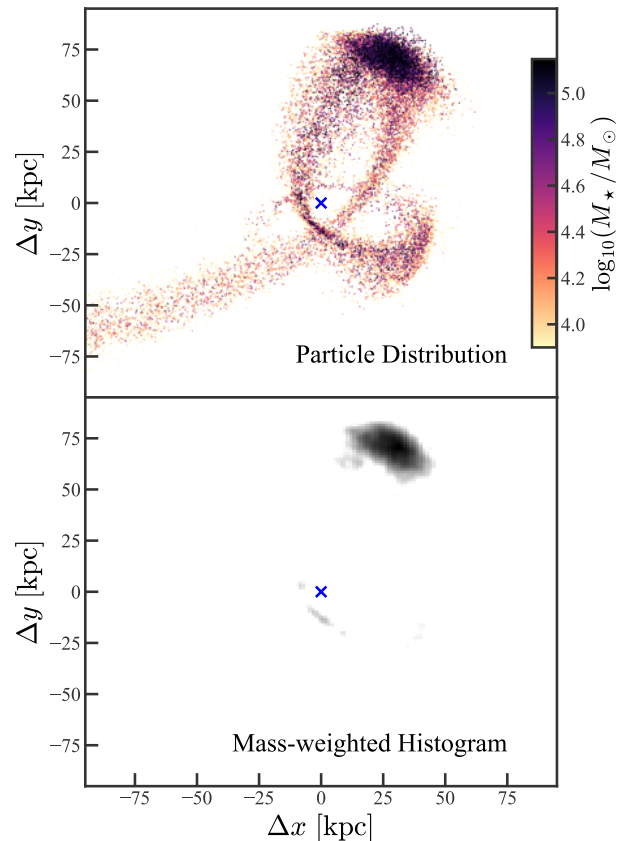

Fig. 4. *Top:* Particle positions of satellite number 11 in halo 15 from the stellar halo models of Bullock & Johnston (2005). Particle stellar masses are indicated by color, and the blue cross marks the location of the Milky-Way-like host galaxy. *Bottom:* Mass-weighted histogram of the particle distribution smoothed with a Gaussian kernel and shown on an arbitrary logarithmic scale. Assuming a constant mass-to-light ratio, this roughly represents a possible observation of this satellite. Although the scale is arbitrary, it demonstrates that it is possible to create a structure similar to Sumo Puff in a merger event with all evidence of a tidal stream hidden below an instrument's detection limits and/or behind the main galaxy. Note this figure is meant to provide a qualitative example of a plausible merger geometry and is not an attempt to model the full details of the merger seen in Figure 1.

shell-like structures viewed from most angles have caustic-like features or sharp edges in their surface brightness profiles, unlike Sumo Puff.

To investigate the possibility of forming an apparently caustic-free, isolated stellar cloud similar to Sumo Puff via the accretion of a satellite, we use a stellar halo model (halo 15) from the Bullock & Johnston (2005) simulations[3] (note that here we are only considering Sumo Puff and not the pronounced shell and more compact tidal features apparent in the main galaxy). These models use a hybrid N-body and semi-analytic approach to study the build-up of stellar halos of Milky-Way-like galaxies through the disruption and accretion of satellite galaxies within the ΛCDM cosmological context. For full de-

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[3] The models are available at `http://user.astro.columbia.edu/~kvj/halos/`.
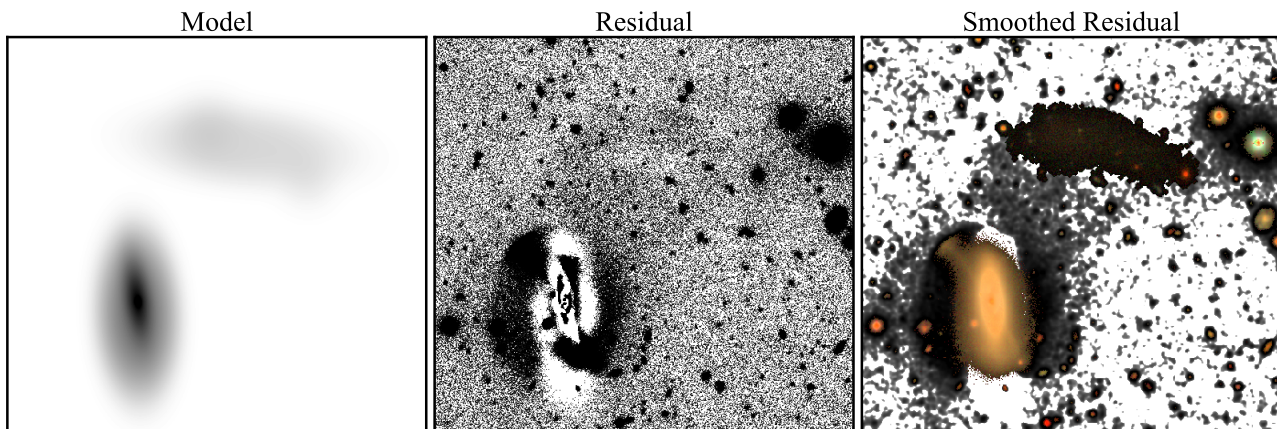
Fig. 5. Tentative evidence of a bridge of low-surface-brightness material connecting Sumo Puff and SDSS J1449-0042. We show a model of both objects (left), the residual image after subtracting this model from the i-band image (middle), and the residual image smoothed with a Gaussian kernel to accentuate faint structures (right). We have overlaid sources from the gri-composite image on the smoothed residual image to help guide the eye.

tails of the methods used in these simulations, see Bullock & Johnston (2005), Robertson et al. (2005), and Font et al. (2006).

For our purposes, we are simply interested in finding an accretion event that, when viewed from a particular angle, creates a structure that is qualitatively similar to Sumo Puff. Note that we are not attempting to model the full details of the merger seen in Figure 1; rather, our aim is to provide a qualitative example of a possible merger geometry. In the top panel of Figure 4, we show the particle positions of satellite number 11 projected onto the two-dimensional viewing plane. Particle stellar masses, which are indicated by color, are not uniform due to the particle tagging method used in Bullock & Johnston (2005). This satellite's initial stellar mass was $\log_{10}(M_\star/M_\odot) \sim 8.8$. The blue cross marks the location of the host galaxy. In the bottom panel, we show a mass-weighted, two-dimensional histogram of the particle positions on an arbitrary logarithmic scale. Assuming a constant mass-to-light ratio (not a great assumption, but likely good enough for the point being made here), mass is proportional to flux, and this histogram roughly represents what one might see in an observation of this satellite. Although the scaling is arbitrary, it nevertheless demonstrates that there is a scale (set by the detection limits of the observation) at which a caustic-free, isolated stellar cloud will be visible with essentially all evidence of a tidal stream hidden below the instrument's detection limits and/or behind the main galaxy.

We note that the combination of Sumo Puff and the sharp shell-like feature in the upper-left region of the post-merger SDSS J1449-0042 (see Figure 1) is still quite puzzling, since both structures appear on the same northern side of the main galaxy. This may suggest that they are due to a single merger event, but it is also possible that they were created during independent merger events. However, as Figure 4 demonstrates, projection effects combined with surface brightness limits can produce non-intuitive geometries, which are difficult to under-

stand without the aid of more tailored simulations. We, therefore, remain agnostic about whether a single or multiple merger events are responsible for the morphology of this system.

Close inspection of the images shown in Figures 1 and 2 reveals a possible bridge of low-surface-brightness material connecting Sumo Puff and SDSS J1449-0042. If this feature is real, it would strongly support the tidal scenario. To ensure that we are not simply observing the overlapping isophotes from these two sources, we subtract a model of both objects from the i-band image to reveal faint structures that are hidden below the dominant components of the light profiles. For Sumo Puff, we use the multi-component model presented in Section 3.1. For SDSS J1449-0042, we again use *imfit* to fit the galaxy's surface brightness profile with a multi-component model consisting of two Sérsic functions and a Gaussian function at the center of the galaxy. When performing the fits, we mask sources (including the sharp shell-like feature on the upper-left of the galaxy) that are not associated with the galaxy's smooth light profile.

The results are shown in Figure 5. In the left panel, we show the combined model for Sumo Puff and SDSS J1449-0042. In the middle panel, we show the residuals after subtracting this model from the i-band image. Within the main galaxy, we see fine structure that is associated with its merger history and morphological properties that are not captured by our simple model. In addition, there is a hint of a bridge between the two objects. To emphasize this feature, we smooth the residual image with a Gaussian kernel with a full width at half maximum of $0.8''$ (slightly larger than the PSF). We show the smoothed residual image in the right panel with sources from the gri-composite image overlaid for reference. The smoothing accentuates the low-surface-brightness bridge, which provides tentative evidence in support of the tidal scenario for Sumo Puff. Deeper images could confirm the presence of this bridge material and would argue strongly that Sumo Puff is tidal.

Considering the evidence presented in this section, we favor a scenario in which Sumo Puff is tidal debris from a satellite that is being accreted by SDSS J1449-0042. This accretion event is not necessarily associated with the more compact tidal features that are clearly present in SDSS J1449-0042.

4.2 Disturbed ultra-diffuse galaxy

In this alternative scenario, Sumo Puff is a dwarf galaxy, whose red color suggests it is a satellite of a massive companion (Geha et al. 2012). As described in Section 3.2, we have selected three potential host galaxies that fall within the redshift range $0.0055 < z < 0.0431$, corresponding to a comoving distance range ~24–180 Mpc. At the low end of this distance range, Sumo Puff would have an effective radius $r_{eff} \sim 1.5$ kpc and absolute i-band magnitude $M_i \sim -12.9$ mag, which is consistent with the size-luminosity relation for dwarf/ultra-diffuse galaxies (e.g., Muñoz et al. 2015). Using the same mass-to-light ratio/color relation derived from Bell et al. (2003) above, this implies a stellar mass $M_\star \sim 2.0 \times 10^7\ M_\odot$. With a central g-band surface brightness of ~26.4 mag arcsec^{-2}, these physical properties would classify Sumo Puff as an ultra-diffuse galaxy. In addition, Sumo Puff's lumpy and elongated morphology would suggest it is being tidally disrupted, possibly similar to objects recently discovered around the massive ellipticals NGC 5485 and NGC 5473 at a similar distance from the Milky Way (Merritt et al. 2016b). There are also similarities with the only known ultra-diffuse galaxy in the Local Group, And XIX (McConnachie et al. 2008), which is ~187 kpc from M31 and is known to be disrupting (Collins et al. 2013).

Our diffuse-galaxy search covered ~100 deg^2 at the time of Sumo Puff's discovery. Given this small search area and the little volume that is probed out to $z = 0.0055$ (the lowest redshift in our assumed range), how many Sumo Puff-like galaxies with $z < 0.0055$ do we expect in our sample? Assuming the luminosity function of Blanton et al. (2005), which explicitly corrects for low-surface-brightness galaxies, we expect our sample to contain ~0.5 galaxies with absolute magnitude and surface brightness comparable to Sumo Puff (assuming $z = 0.0055$). However, this expectation is based on a large extrapolation, since our object is nearly a magnitude fainter than the faintest luminosities in the Blanton et al. (2005) study, and its surface brightness is well below the limits of their survey. With the imaging of HSC-SSP, we are beginning to push down into this relatively unexplored region of parameter space, which will enable the extension of the luminosity function of field galaxies down to such low luminosities.

In this dwarf-galaxy scenario, Sumo Puff's physical properties become increasingly extreme with increasing redshift. At the high end of the assumed redshift range ($z = 0.0431$), its properties would be the same as given in the above tidal sce-

nario: $r_{eff} \sim 11$ kpc and $M_i \sim -17.4$ mag. These properties would make it somewhat of an outlier in the size-luminosity relation for galaxies, with a size comparable to the most extreme ultra-diffuse galaxies known, VLSB-A and VLSB-D in the Virgo cluster (Mihos et al. 2015; Mihos et al. 2017), which are also thought to be undergoing tidal disruption. However, assuming a redshift of $z = 0.0431$, Sumo Puff's total luminosity would be ~2 magnitudes brighter than these objects.

5 Discussion and Conclusions

We have reported the discovery of a potentially giant, low-surface-brightness stellar cloud (Sumo Puff), which is in close proximity on the sky to the post-merger galaxy SDSS J144916.46-004240.5 (SDSS J1449-0042; Figure 1). We discovered this remarkable object during the development of our automated pipeline to detect diffuse galaxies in the wide layer of HSC-SSP. We offer two possible interpretations for the nature of Sumo Puff: (1) it is an extreme, galaxy-size tidal feature produced by a recent merger event with SDSS J1449-0042, or (2) it is a disturbed ultra-diffuse galaxy in the redshift range $0.0055 < z < 0.0431$, with properties that become increasingly extreme with increasing redshift. Because of Sumo Puff's close angular proximity to SDSS J1449-0042, its lumpy and elongated morphology (Table 1 and Figure 2), qualitative similarities to merger simulations (Figure 4), and the potential bridge of low-surface-brightness material connecting Sumo Puff and SDSS J1449-0042 (Figure 5); we prefer the tidal debris scenario. In this scenario, Sumo Puff may or may not be the result of the same accretion event that caused the pronounced shell and more compact tidal features apparent in SDSS J1449-0042. A distance measurement and/or deeper imaging to confirm the existence of the bridge material will be necessary to reveal the true nature of Sumo Puff.

If our interpretation is correct, we are watching the halo of this galaxy being built. This finding demonstrates the potential of deep *and* wide surveys to inform theories of galaxy formation by testing the predictions of hierarchical growth of structure in a ΛCDM universe. Upon completion, the wide layer of HSC-SSP will reach depths of $i \sim 26$ over 1400 deg^2. Using reduced HSC-SSP (full survey depth) images, which have not been optimized for low-surface-brightness science, we are currently detecting objects with central surface brightnesses as low as $\mu_0(i) \sim 26.5$–27 mag arcsec^{-2} (Greco et al. in prep.) and the outskirts of massive ellipticals have been measured down to $\mu(i) \sim 28.5$ mag arcsec^{-2} (Huang et al. in prep.). Simulations predict that the halos of massive galaxies are rich with substructure at these surface brightnesses (Johnston et al. 2008). Therefore, the full HSC-SSP data set will have the potential to provide a statistical sample of extragalactic tidal streams and Sumo Puff-like objects, which can, in principle, reveal prop-

erties of the underlying population of satellites that are being accreted to form the halos of massive galaxies.

Sumo Puff was discovered as part of our ongoing search for ultra-diffuse galaxies outside of cluster environments. If it is in fact tidal in nature, then it is a scientifically interesting contaminant in our search. As the discovery space of these elusive galaxies pushes down to lower-density environments, it will become increasingly important to understand all potential sources of contamination. As Sumo Puff demonstrates, confusion between tidal debris and disrupting dwarf galaxies may be significant. For example, some of the objects discovered by Merritt et al. (2016b) may actually be tidal in origin. On the other hand, if Sumo Puff is a foreground dwarf galaxy, it is a very nearby example of an ultra-diffuse galaxy with interesting morphological properties.

Acknowledgments

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