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Satellite accretion in action: a tidally disrupting dwarf spheroidal around the nearby spiral galaxy NGC 253

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ABSTRACT

We report the discovery of NGC 253-dw2, a dwarf spheroidal (dSph) galaxy candidate undergoing tidal disruption around a nearby spiral galaxy, NGC 253 in the Sculptor group: the first such event identified beyond the Local Group. The dwarf was found using small-aperture amateur telescopes, and followed up with Suprime-Cam on the 8 m Subaru Telescope in order to resolve its brightest stars. Using *g*- and *R_c*-band photometry, we detect a red giant branch consistent with an old, metal-poor stellar population at a distance of ~ 3.5 Mpc. From the distribution of likely member stars, we infer a highly elongated shape with a semimajor axis half-light radius of (2 ± 0.4) kpc. Star counts also yield a luminosity estimate of $\sim 2 \times 10^6 L_{\odot,V}$ ($M_V \sim -10.7$). The morphological properties of NGC 253-dw2 mark it as distinct from normal dSphs and imply ongoing disruption at a projected distance of ~ 50 kpc from the main galaxy. Our observations support the hierarchical paradigm wherein massive galaxies continuously accrete less massive ones, and provide a new case study for dSph infall and dissolution dynamics. We also note the continued efficacy of small telescopes for making big discoveries.

Key words: galaxies: dwarf – galaxies: individual: NGC 253 – galaxies: interactions.

1 INTRODUCTION

The modern paradigm of cold dark matter with a cosmological constant (Λ CDM) predicts that galaxies form hierarchically – growing through the gradual merging of many smaller galaxies. A giant spiral like our Milky Way is expected to undergo a succession of dwarf galaxy accretion events which have different observational signatures, depending on their occurrence in the past, present, or future. Ancient accretion events can be detected through careful sifting of the chemo-dynamical phase-space of halo stars. Ongoing accretion is implied by the presence of satellite galaxies within the halo, and imminent accretion is marked by the existence of field dwarfs near to their future hosts.

All of these manifestations of accretion are the focus of intense inventory and scrutiny, in order to compare observations to theory. In particular, there is a long-running concern about the relative scarcity of Milky Way satellites, more recently expressed as a ‘too big to fail’ problem (see summary in Weinberg et al. 2013). There is also a recent controversy about the coherence of observed satellite systems compared to expectations of more random infall (e.g. Pawlowski, Pflamm-Altenburg & Kroupa 2012; Ibata et al. 2013; Sawala et al. 2015). These tensions between observation and theory have led to doubts about the standard model – with solutions ranging from baryonic feedback to mild revisions of the dark matter theory to radical dismissal of the entire cosmological framework (e.g. Kroupa 2012; Brooks & Zolotov 2014).

In this context, intense observational efforts continue to focus on inventories and analyses of satellites and streams around the Local Group (e.g. Whiting et al. 2007; McConnachie et al. 2009; Bechtol

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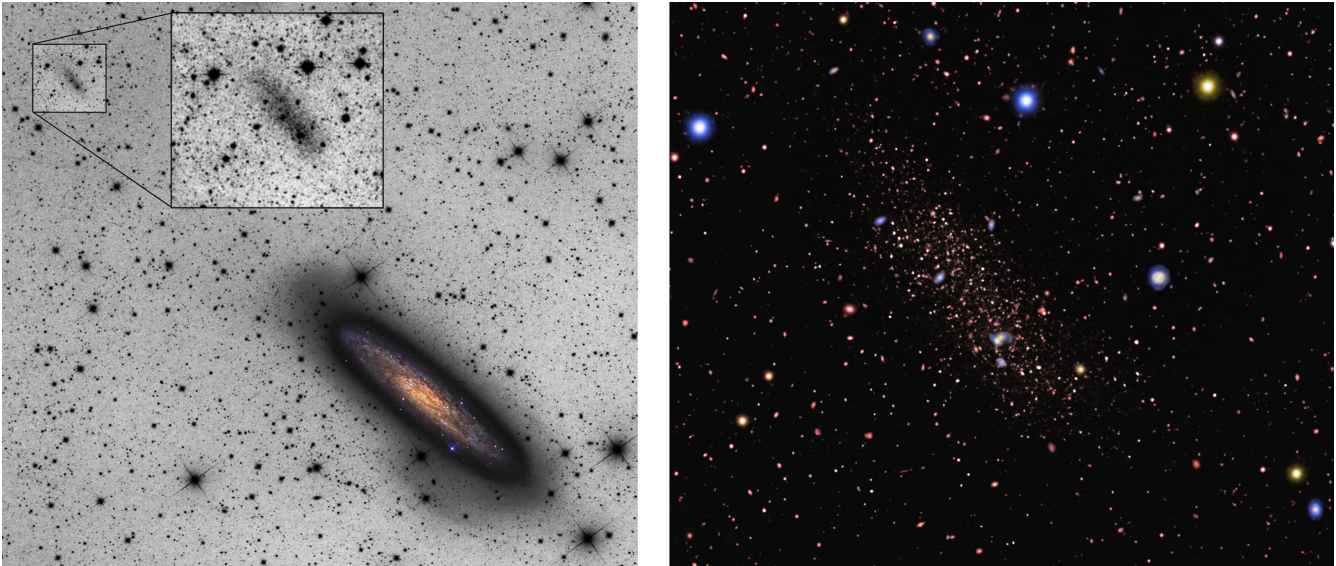


Figure 1. Left: amateur images of NGC 253 and its satellite NGC 253-dw2. The grey-scale image is from the 12-in telescope luminance filter, with colour image of NGC 253 from the 0.5 m Black Bird Remote Observatory, and field of view of $\sim 1^\circ 1' \times 1^\circ 0'$ (67 kpc \times 60 kpc). North is up and east is left. The zoom-in on NGC 253-dw2 is from CHART32 and covers ~ 8 kpc \times 7 kpc. Right: Subaru/Suprime-Cam image, colourized using g and R_c bands, and demonstrating that the satellite is composed of red, discrete stars.

et al. 2015). More challenging but essential to a full picture is the extension to studying a broader sample of galaxies at larger distances. Success has been obtained through low-surface brightness imaging and resolved stellar maps (e.g. Merritt, van Dokkum & Abraham 2014; Okamoto et al. 2015; Müller, Jerjen & Binggeli 2015), but the work is far from complete.

One valuable, alternative route to finding faint satellites and streams around nearby galaxies is through using small aperture (10–50 cm) telescopes in combination with the latest generation of commercial CCD cameras (e.g. Martínez-Delgado et al. 2012, 2015; Javanmardi et al. 2015; Karachentsev et al. 2015). The short focal ratios of these telescopes, along with the use of single, photographic-film size CCDs, allow them to probe large areas of galaxy haloes while reaching surface brightness levels ~ 2 – 3 mag deeper ($\mu_r \sim 28$ mag arcsec $^{-2}$) than the classic photographic plate surveys (e.g. Palomar Observatory Sky Survey) and the available large-scale digital surveys (e.g. the Sloan Digital Sky Survey).

Here, we use this amateur telescope discovery approach to report a faint, elongated galaxy projected on to the halo regions of NGC 253 in the Sculptor Group. With a distance of 3.5 Mpc, NGC 253 is one of the nearest large spirals, and has been well studied (e.g. Davidge 2010; Bailin et al. 2011; Greggio et al. 2014; Monachesi et al. 2015), but this object, which we call NGC 253-dw2, had been missed.¹

2 OBSERVATIONS

We first noticed a candidate satellite galaxy in a visual inspection of several images of NGC 253 available on the internet that were taken by amateur astronomers: Alessandro Maggi using a Takahashi Epsilon 180ED astrograph (18-cm diameter at $f/2.8$) and Mike Sidonio using a 12-in $f/3.8$ Newtonian (see Fig. 1). In both cases,

the pixel scale was coarse and it was not clear if the elongated feature was real or an artefact or reflection as often present in amateur images.

We investigated the nature of NGC 253-dw2 by follow-up observations using amateur and professional facilities as follows. First, deep imaging of the field centred on the dwarf candidate was collected remotely with the Chilean Advanced Robotic Telescope (CHART32), an 80-cm $f/7$ corrected Cassegrain telescope located at the Cerro Tololo Inter-American Observatory, Chile. An FLI PL-16803 CCD camera was used, with a pixel scale of 0.331 arcsec over a 22 arcmin \times 22 arcmin field-of-view. Two overlapping sets of 20 \times 1200 s individual image frames were obtained through a Baader luminance filter over several photometric nights between 2013 September and November. Each individual exposure was reduced following standard image processing procedures for dark subtraction, bias correction, and flat-fielding (Martínez-Delgado et al. 2010). The images were combined to create a final co-added image with a total exposure time of 48 000 s.

Part of the resulting CHART32 image is shown as an inset in Fig. 1 (left-hand panel). The candidate object looks fairly regular and diffuse, like a nearby dwarf spheroidal (dSph) galaxy rather than a background galaxy or an instrumental artefact. It is also very elongated, and could in principle be a clump of foreground Galactic cirrus, although there are no such indications from the *Planck* 857 GHz data.

To investigate further, we used the Suprime-Cam imager on the 8 m Subaru telescope (Miyazaki et al. 2002), with 5 \times 114 s of g -band imaging on 2014 December 18, and 5 \times 120 s of Johnson–Cousins R_c -band on 2014 December 19 (filters dictated by observing schedule constraints). The seeing was ~ 0.8 and ~ 0.95 arcsec in g and R_c , respectively. The data were reduced using a modified version of the SDFRED-2 pipeline.²

Pre-processing of the Suprime-Cam data was done by debiasing, trimming, flat-fielding, and gain correcting each individual

¹ During the preparation of this paper, we learned of an independent discovery of the same object, using the 6.5 m Magellan telescope (Toloba et al. 2016).

² <http://tinyurl.com/SDFRED2>

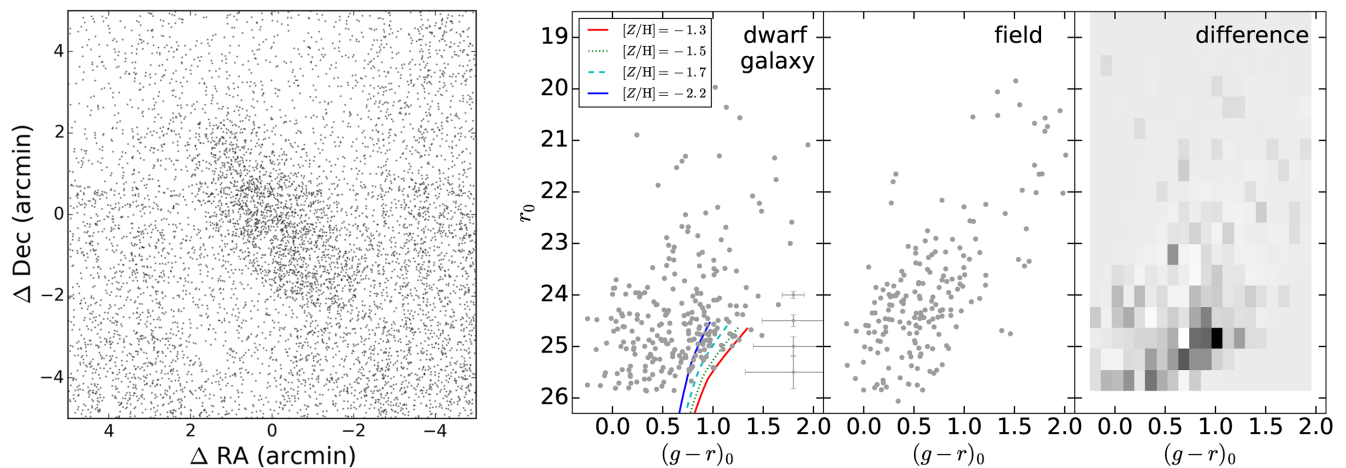


Figure 2. Resolved stars in NGC 253-dw2, from Subaru/Suprime-Cam R_c -band photometry. Left: star map in a 10 arcmin (10 kpc) square region. The dwarf galaxy emerges as an overdensity of stars against a uniform background of contaminants, and its elongated shape confirms the appearance in the amateur images (Fig. 1, left). Right: colour–magnitude diagram for the dwarf (left), compared to an equal-area control field (middle). The binned difference between the dwarf field and a larger-area control field (for better statistics) is shown on the right. Curves show 13-Gyr isochrones from PARSEC (Bressan et al. 2012), with metallicities as in the legend.

exposure chip-by-chip using median stacks of nightly sky flats. Scattered light produced by bright stars both in and out of the field of view required removing this smoothly varying component before performing photometry and solving for a World Coordinate System solution. To remove scattered light, we fitted the smoothly varying component by creating a flat for every chip within each frame using a running median with a 300 pixel box-size. This was then subtracted from the original, unsmoothed frame to produce a final image for photometric processing.

Fig. 1 (right-hand panel) shows a portion of the Suprime-Cam image around NGC 253-dw2. Again, the object appears elongated, but now is visibly resolved into stars – with an appearance similar to another Suprime-Cam image of a disrupted dSph at ~ 4 Mpc (Martínez-Delgado et al. 2012).

The Suprime-Cam instrumental magnitudes were derived using the DAOPHOT II and ALLSTAR (Stetson 1987) packages. Sources were detected in the g -band by requiring a 3σ excess above the local background, with the list of the g -band detections being subsequently used for the ALLSTAR run on the R_c -band image. To obtain clean colour–magnitude diagrams and to minimize contamination from faint background galaxies, sources with the ratio estimator of the pixel-to-pixel scatter $\chi < 2.0$ and sharpness parameters $|S| < 1.0$ (see Stetson 1987) were kept for further analysis. To calibrate the photometry, we cross-identified sources from Subaru with Pan-STARRS1 sources for which the photometric uncertainties are lower than 0.05 (Schlafly et al. 2012; Tonry et al. 2012; Magnier et al. 2013). There is no strong evidence of a significant colour term between the Subaru and Pan-STARRS1 filters (g versus g , R_c versus r), so we used the median magnitude offset to calibrate the Subaru data on to the Pan-STARRS1 photometric system.

3 COLOUR–MAGNITUDE DIAGRAM AND STRUCTURAL ANALYSIS

We now consider some properties of NGC 253-dw2 using the Suprime-Cam resolved stellar photometry. Stars are selected from an elliptical region of ~ 5 arcmin \times 18 arcmin around this galaxy (Fig. 2, left-hand panel) and plotted on an extinction-corrected colour–magnitude diagram (right). For comparison, we also show a

control field with an equal area but ~ 4 arcmin away from the dwarf. Relative to the control field, the dwarf field has an overdensity of stars at roughly $r_0 \sim 25$, $(g-r)_0 \sim 1.0$. This is just the signature expected for the upper regions of the red giant branch (RGB) at a distance of ~ 3.5 Mpc – based both on other observations of NGC 253 (Sand et al. 2014) and on theoretical isochrones (also shown in Fig. 2).

The presence of the RGB stars implies an age of more than 1 Gyr, and the isochrone comparisons suggest a metallicity of $[Z/H] \sim -2.0 \pm 0.5$. There are no obvious signs of blue main-sequence or of core-helium burning ‘blue loop’ stars, which would trace star formation over the past 600 Myr. The dwarf thus appears similar to the old, metal-poor halo population of NGC 253 (cf. Radburn-Smith et al. 2011; Monachesi et al. 2015), although the shallowness of the imaging makes it difficult to definitively rule out the presence of some young stars, or of asymptotic giant branch stars from an intermediate-age population, as found in another satellite of NGC 253, Scl-MM-Dw1 (Sand et al. 2014). Therefore, the possibility remains that it is a dSph–dlrr transition type.

The structural parameters of the dwarf galaxy are determined through modelling the spatial distribution of its stars, assumed to follow an exponential density profile. We use the algorithm developed in Martin, de Jong & Rix (2008) and updated with a full Markov Chain Monte Carlo treatment. The posterior probability density function (PDF) is produced for six model parameters (plus a constant background level): the spatial centroid of the dwarf, its semimajor axis half-light radius a_h , its ellipticity ϵ , the major axis position angle θ , and the number of stars N_* in the galaxy (down to a magnitude of $r_0 = 25.3$; the shallower g -band imaging is not used).

The resulting marginalized PDFs are in Fig. 3 (left) for the three main parameters of interest (ϵ , θ , and a_h) and summarized in Table 1. The new dwarf galaxy is very elongated: $\epsilon \sim 0.6$ – 0.7 . Its implied physical size is $a_h = (2.0 \pm 0.4)$ kpc or $R_h = (1.1 \pm 0.2)$ kpc circularized (geometric mean of major and minor axes; including a small uncertainty on the distance modulus, $m - M = 27.7 \pm 0.1$, from an adopted thickness of ~ 150 kpc for the NGC 253 satellite distribution). Its total luminosity is estimated as follows. We begin populating an artificial stellar luminosity

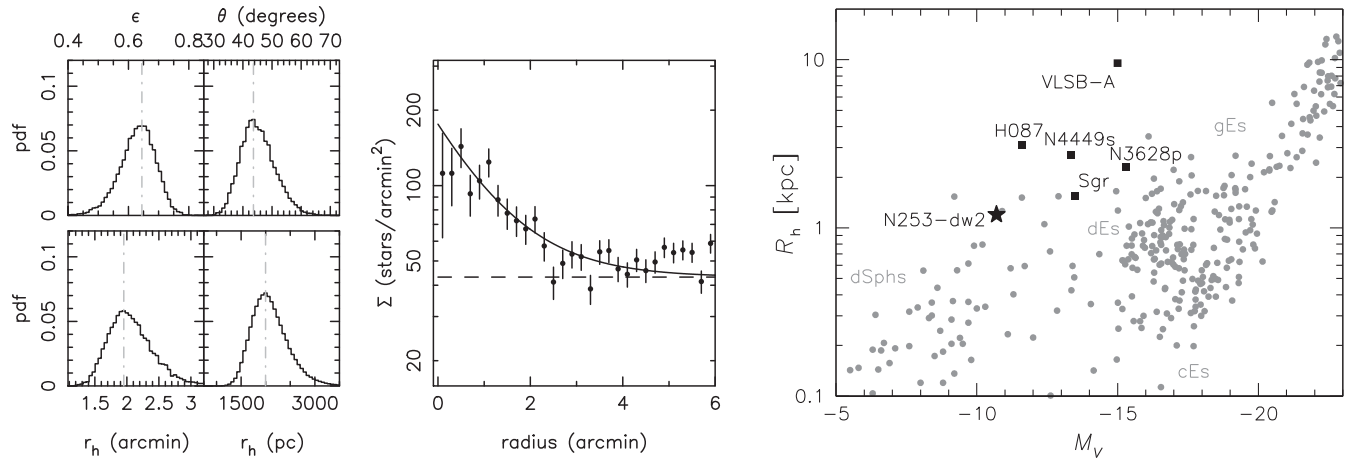


Figure 3. Left: structural parameters of NGC 253-dw2, from modelling star counts, and expressed as probability density functions. Middle: model fit to star counts versus semimajor axis radius; the dashed line marks the background level. Right: circularized half-light radius versus absolute magnitude for hot stellar systems. NGC 253-dw2 (red star) has a large size for its luminosity. Black squares mark other disrupting dwarfs (Koch et al. 2012; McConnachie 2012; Martínez-Delgado et al. 2012; Jennings et al. 2015; Mihos et al. 2015).

Table 1. Properties of NGC 253-dw2.

Property	Value
α (J2000)	00:50:17.9 ^{+0.5} _{-0.6}
δ (J2000)	-24:44:25.8 ^{+6.7} _{-8.4}
Ellipticity ϵ	0.64 ^{+0.05} _{-0.07}
Position angle (deg E of N)	44 \pm 6
M_V	-10.7 \pm 0.4
a_h (arcmin)	2.0 ^{+0.4} _{-0.3}
a_h (kpc)	2.0 \pm 0.4
R_h (kpc)	1.1 \pm 0.2
$\mu_{0,V}$ (mag arcsec ⁻²)	26.2 \pm 0.8

function, based on PAdova and TRieste Stellar Evolution Code (PARSEC) isochrones, until N_* stars fall above the observational threshold of $r_0 = 25.3$. We then sum up the flux of all stars, above and below the threshold, and find a total V -band luminosity of $(1.6 \pm 0.3) \times 10^6 L_\odot$, which is equivalent to $M_V = -10.7 \pm 0.4$ and implies a central surface brightness $\mu_{0,V} = 26.2 \pm 0.8$.

4 DISCUSSION AND CONCLUSIONS

We now place NGC 253-dw2 in a plot of luminosity and size from a compilation of hot stellar systems (Brodie et al. 2011, with updates.³) As Fig. 3 (right) shows, this object is about twice as large as an average dSph of the same luminosity, although there are a few objects with comparable properties – most notably And XIX. The elongated shape is also unusual for a dSph (McConnachie 2012; Sand et al. 2012), and the only known examples in the Milky Way with $\epsilon \geq 0.6$ are all thought to be tidally disrupting (Sgr, Her, UMa I, UMa II; e.g. Muñoz, Geha & Willman 2010).

Tides are predicted to cause elongation – both from unbound stars soon after a pericentric passage (Peñarrubia, Walker & Gilmore 2009), and during the final stage before complete disruption (Muñoz, Majewski & Johnston 2008). We make a rough initial estimate of the tidal radius of NGC 253-dw2, assuming a V -band stellar mass-to-light ratio of ~ 1.5 , and the dark matter largely stripped. At

a galactocentric distance of 50 kpc, we adopt a host galaxy circular velocity of 180 km s⁻¹ (extrapolating from Lucero et al. 2015). Following Muñoz et al. (2008), we predict a ‘limiting’ radius of ~ 1 kpc, which in combination with the observations suggests the dwarf is filling or overfilling its Roche lobe. Five examples of clearly disrupting dwarfs are also marked in Fig. 3 (right), and appear as similar outliers from the mean relation. We conclude, based on the ellipticity and size of NGC 253-dw2, that it is experiencing tidal disruption. In this scenario, the ellipticity of the dwarf may imply that >90 per cent of its stellar mass has been lost (Muñoz et al. 2008), and thus that its pre-disruption luminosity was $\gtrsim 2 \times 10^7 L_\odot$ (equivalent to the Fornax dSph). If spread over a broad region, this large quantity of extratidal stars could well have been missed by our imaging. Although such a luminous progenitor might be in tension with our low-metallicity inference (e.g. Caldwell 2006), we note that photometric errors make this inference very provisional.

The discovery of NGC 253-dw2, and the potential for follow-up observations, provides an opportunity to study the dynamics of a disrupting dSph, to test its dark matter distribution (e.g. McGaugh & Wolf 2010; Errani, Peñarrubia & Tormen 2015) and to compare its infall direction to the large-scale shear field (Libeskind et al. 2015). It may also have implications for the effect of the satellite on the host. Even though this dwarf has a relatively low stellar mass, Λ CDM models predict a pre-infall virial mass of $\sim (1-4) \times 10^{10} M_\odot$ (Tollet et al. 2015). This is similar to the stellar mass of NGC 253 ($1.7 \times 10^{10} M_\odot$; Lucero et al. 2015), and even if 95 per cent of the dark matter was lost before making a close passage to the host, it could still have had a noticeable impact. Intriguingly, NGC 253 has several peculiar features (central starburst, kinematic twisting, stellar halo ‘shelf’ – also visible in Fig. 1) previously suggested as signatures of recent, unidentified interactions (e.g. Davidge 2010). It is possible that the culprit has now been found, and that more cases of dwarf-galaxy ‘stealth attacks’ could be identified through deep, wide-field studies of galaxy haloes.

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³ http://sages.ucolick.org/spectral_database.html

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