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A tidally distorted dwarf galaxy near NGC 4449

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NGC 4449 is a nearby Magellanic irregular starburst galaxy[1] with a B-band absolute magnitude of −18 and a prominent, massive, intermediate-age nucleus[2] at a distance from Earth of 3.8 megaparsecs (ref. 3). It is wreathed in an extraordinary neutral hydrogen (H I) complex, which includes rings, shells and a counter-rotating core, spanning ∼90 kiloparsecs (kpc; refs 1, 4). NGC 4449 is relatively isolated[5], although an interaction with its nearest known companion—the galaxy DDO 125, some 40 kpc to the south—has been proposed as being responsible for the complexity of its H I structure[6]. Here we report the presence of a dwarf galaxy companion to NGC 4449, namely NGC 4449B. This companion has a V-band absolute magnitude of −13.4 and a half-light radius of 2.7 kpc, with a full extent of around 8 kpc. It is in a transient stage of tidal disruption, similar to that of the Sagittarius dwarf[7] near the Milky Way. NGC 4449B exhibits a striking S-shaped morphology that has been predicted for disrupting galaxies[7,8] but has hitherto been seen only in a dissolving globular cluster[9]. We also detect an additional arc or disk ripple embedded in a two-component stellar halo, including a component extending twice as far as previously known, to about 20 kpc from the galaxy's centre.

We obtained deep imaging of NGC 4449 during the time period 29 May 2011 to 1 June 2011, in the course of commissioning a 0.7-m telescope[10] designed to study low-surface-brightness structures in the vicinity of other galaxies. We discovered the profoundly tidally distorted dwarf galaxy NGC 4449B, and recover an additional lower-luminosity arc or disk ripple, deeper in its halo (Fig. 1). Our photometry reveals that the original exponential halo terminates in a dumb-bell-shaped shelf, beyond which we measure a de Vaucouleurs $r^{1/4}$ surface brightness profile to 20 kpc (here r is the angular distance from the centre of NGC 4449). (Figs 1 and 2). Although we do not measure a change in the $g - r$ colour of the outer halo, the break in structure might imply a different origin for the $r^{1/4}$ component.

The lower-luminosity arc or ripple mentioned above is revealed by subtracting a model halo profile, but can also be clearly seen in unprocessed images (Fig. 1) and is also faintly visible and noted in earlier images[1]. However, we detect no additional components of a putative shell system as might be expected if this arc were part of a typical shell complex (even induced via an unusual collision geometry[11,12]). The arc or ripple might plausibly be a disk ripple, owing its origin to the interaction with NGC 4449B or a different event[13]. The ripple is

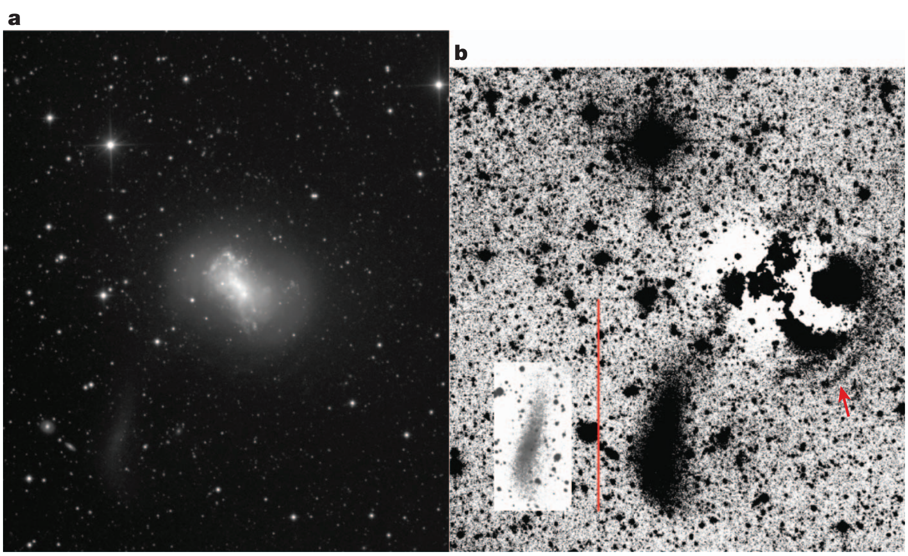

Figure 1 | Image and halo-subtracted imagery of NGC 4449. **a**, Positive image of NGC 4449 and NGC 4449B. (This is a 3.2-h luminance filter image from an STL 11000m camera, obtained using the Saturn Lodge 0.7-m Centurion[10] telescope.) **b**, Image (same scale as **a**) obtained by subtracting from **a** a model halo, using ELLIPSE within IRAF. Image shows detail of NGC 4449B, including a plume extended northwestwards towards the nucleus of NGC 4449. Inset, a softer stretch, revealing the S-shape distortion characteristic of a galaxy that has undergone tidal disruption. The fainter arc/disk ripple (indicated with a red arrow) can be easily seen to the southwest of the nucleus, and can be recovered as well in **a**. The arc/ripple lacks the edge or counter-arc structures characteristic in classical shells. A well defined shelf in the halo of NGC 4449 is evident in **a** and can be clearly seen in the surface brightness profile of Fig. 2. North is up, east is left. The red scale bar is 10 arcmin = 11.11 kpc, adopting a distance[1] of 3.82 Mpc for NGC 4449. Integration times were 3.2 h in a broadband Astrodon I-series Luminance (L) filter and 45 min each in the B and R filters. The wide L filter is a square pass filter spanning 400–700 nm that yields the deepest images, while the B and R filters are square pass filters covering 400–500 nm and 600–700 nm, respectively. Because NGC 4449 is within the SDSS footprint, we use catalogued SDSS stars to calibrate B and R to SDSS g and r photometry. The total r magnitude for NGC 4449B was obtained by calibrating the L filter to SDSS r with the total magnitude from ELLIPSE, after subtracting stellar sources from the footprint of the dwarf.

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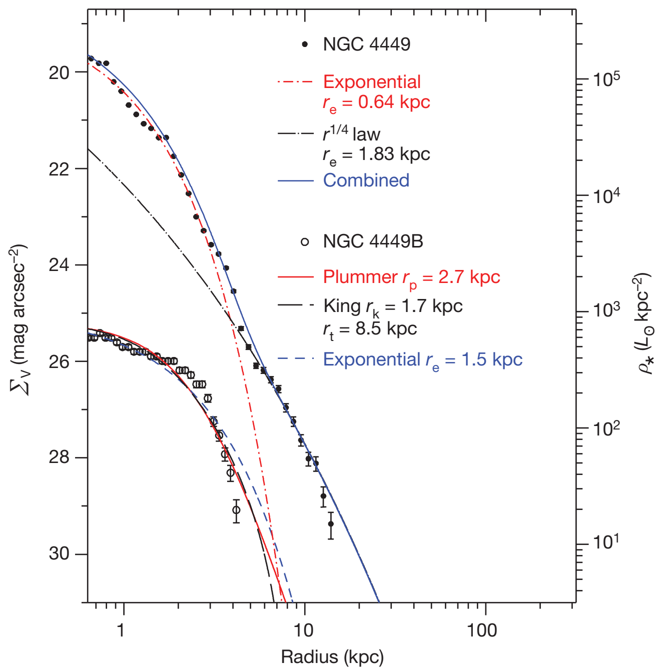

Figure 2 | Surface photometry of NGC 4449 and NGC 4449B. Surface brightness profiles (data points) and model fits (solid and broken lines) for the halo of NGC 4449 and for NGC 4449B. Σ_V is the surface brightness, ρ_* is the stellar surface density, and $L_\odot$ is solar luminosity. The halo of NGC 4449 exhibits a dumb-bell-shaped shelf (Fig. 1) at 5 kpc, coinciding with the break in the surface brightness profile. The inner portion of NGC 4449 is best fitted by an exponential[5] with $r_e = 0.64$ kpc and the outer envelope by an $r^{1/4}$ law with $r_e = 1.83$ kpc that can be traced to 20 kpc radius (here r_e is the de Vaucouleurs half-light enclosed or effective radius). Beyond 3 kpc the halo colour is $g - r = 0.5$, similar to that of the dwarf, and we do not detect any change in $g - r$ colour at the shelf; position angle and ellipticity change at the boundary of the outer halo. The exponential portion may be related to the bar, while the outer halo may have an accretion origin. NGC 4449B has a Plummer half-light radius of $r_p = 2.7$ kpc, but we are unable to find any analytical profile that provides a good fit, consistent with a system undergoing tidal disruption[7]. (We include for information the attempted fit to the King profile, with scale radius r_k and tidal radius r_t.) Error bars, s.d.

2.6 kpc long with an r-band magnitude of 19.1 (corresponding to an absolute magnitude $M_r = -8.91 \pm 0.1$, faint even relative to Milky Way dwarfs); our halo subtraction uncovered no additional arcs or candidate dwarfs.

NGC 4449B (also known as NGC 4449 J1228.8+4357.8) lies at a projected distance of 9 kpc from the nucleus of NGC 4449 at right ascension (2000) 12 h 28 min 45 s, declination (2000) +43° 57′ 44″, which is 39.8″ E and 8′ 07.2″ S of the nucleus. The halo model subtraction in Fig. 1 reveals the complete extent of the dwarf, including a plume of faint emission extending northwest towards the nucleus. We derive $r = 14.47 \pm 0.1$ mag and adopting $(m - M)_o = 27.91$ (ref. 3), calculate $M_r = -13.44 \pm 0.1$ mag. The colour of $g - r = 0.48 \pm 0.22$ is that of a non-star forming dwarf galaxy, consistent with the lack of structure at this location in published H I maps[1,4] and non-detection on archival GALEX[14] satellite images of 3,283 s duration in the near-ultraviolet and 1,685 s in the far-ultraviolet. It is noteworthy that the position of NGC 4449B misses by >3 kpc any catalogued[1] H I cloud or shell, although the position falls on the southern edge of the main H I ring[4]. Although GALEX far-ultraviolet imaging usually detects stellar emission in H I tidal tails[15], the extensive H I complex near NGC 4449 is surprisingly undetected in the GALEX imagery. DDO 125 ($M_V = -15.57$) is detected easily in H I and GALEX near- and far-ultraviolet[16], but is disjoint from the main H I complex and, lying 31 kpc to the south of NGC 4449B, is uninvolved with the dwarf. Optical emission from NGC 4449B is traceable to a full extent of 2.65′ × 4.0′ or 2.9 × 7.4 kpc in extent; we calculate a stellar mass[17] of 3.5×10^7 solar masses.

The S-shaped morphology qualitatively resembles a model[7] that places a dwarf galaxy on a highly eccentric orbit, and tracks its evolution from encounter through the close approach of the dwarf galaxy (the 'impactor') to the nucleus of the primary galaxy. Such extreme orbits are proposed for other systems: for example, And XIV has kinematics consistent with a first-encounter plunge orbit with M31 (ref. 18). NGC 4449B appears to fall somewhere between time steps 2 and 3 (as shown in figure 1 of the simulation reported in ref. 7), or ~5–10 crossing times past closest approach between the dwarf and nucleus, a point in the simulation where most of the dark matter still remains bound to the dwarf. The encounter geometry that we observe for NGC 4449B is also consistent with the modelled timescale[7] over which the dwarf evolves from a compact spheroid to the 'nucleus and tails' morphology prominent in the disrupted globular cluster Palomar 5[8,9]. The width of the dwarf galaxy's central region (28″ = 516 pc) constrains a length scale for the pre-encounter system even though we do not discern the nucleus. If we adopt an effective radius of ~200 pc for the pre-tidal dwarf and internal velocity dispersion $\sigma = 10$ km s^{-1}, figure 1 of the simulation[7] gives a morphology evolution timescale $t - t_p \approx 10R_c \approx 2 \times 10^8$ yr, where $t - t_p$ is the time since pericentre, or closest encounter, and R_c is the core radius of the dwarf. Assuming that the orbit plane is roughly perpendicular to our sightline (based on the S morphology), we find a timescale of 10^8 yr to traverse 9 kpc at 100 km s^{-1}, in good agreement with the simulation timescale.

We speculate that NGC 4449B is on its first encounter with NGC 4449 and experienced a close passage near the nucleus of NGC 4449. This conclusion is supported by the morphology of NGC 4449B, the plume pointing at the nucleus, and the approximate agreement with the structure and timescales of the simulation[7]. The calculated timescales would not contradict the hypothesis that the NGC 4449B encounter played a role in igniting the present epoch of star formation in NGC 4449. The simulation[7] also predicts that a morphology resembling that of NGC 4449B survives only for a relatively brief interval of ~5 crossing times, or ~10^8 yr, which may, along with its low surface brightness, account for its uniqueness.

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Author Contributions R.M.R. conceived the project, obtained the data and coordinated the activity. M.L.M.C. fitted the surface photometry of NGC 4449 and NGC 4449B. C.M.B., F.M.L. and D.B.R. analysed and reduced various aspects of the dataset, including the surface photometry. F.A.L. and R.M.R. implemented the Saturn Lodge 0.7-m telescope and detector system. A.K. provided insight on dwarf galaxies and discussion, and A.B. provided a discussion of theoretical implications.

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