nature Vol 445|15 February 2007|doi:10.1038/nature05552

LETTERS

Early gas stripping as the origin of the darkest galaxies in the Universe

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The known galaxies most dominated by dark matter (Draco, Ursa Minor and Andromeda IX) are satellites of the Milky Way and the Andromeda galaxies[1–4]. They are members of a class of faint galaxies, devoid of gas, known as dwarf spheroidals[3–5], and have by far the highest ratio of dark to luminous matter[3,6]. None of the models proposed to unravel their origin[7–10] can simultaneously explain their exceptional dark matter content and their proximity to a much larger galaxy. Here we report simulations showing that the progenitors of these galaxies were probably gas-dominated dwarf galaxies that became satellites of a larger galaxy earlier than the other dwarf spheroidals. We find that a combination of tidal shocks and ram pressure swept away the entire gas content of such progenitors about ten billion years ago because heating by the cosmic ultraviolet background kept the gas loosely bound: a tiny stellar component embedded in a relatively massive dark halo survived until today. All luminous galaxies should be surrounded by a few extremely dark-matter-dominated dwarf spheroidal satellites, and these should have the shortest orbital periods among dwarf spheroidals because they were accreted early.

Draco, Ursa Minor and Andromeda IX have mass-to-light ratios (M/L) larger than 100, but the majority of the other dwarf spheroidals in the Local Group have a lower M/L, of order 10–30, (ref. 1) typical among dwarf galaxies[11,12]. Another important difference is that Draco and Ursa Minor nearly stopped forming stars more than ten billion years ago, while other dwarf spheroidals continued to form stars for many billions of years[2]. The modest potential well of these extreme dwarfs cannot be the single property that determined their nature. Their halo masses are too large to invoke suppression of gas accretion owing to the cosmic ultraviolet background at high redshift[9,13] or blow-out due to supernovae winds[14]. Tidal shocks occurring as a dwarf repeatedly approaches the primary galaxy can transform rotationally supported systems resembling dwarf irregular galaxies into systems dominated by random motions, similar to dwarf spheroidals[10]. This tidal stirring can explain why dwarf spheroidals are more clustered around the primary galaxies relative to dwarf irregular galaxies but it leaves a significant gas component inside the dwarf, so that star formation can continue for several billions of years instead of being truncated early. Ram pressure in a hot gaseous corona could strip their gas completely[7,15] but the limitations of simulations so far have not allowed for firm predictions. For instance, existing calculations keep the structure of the stars and halo fixed in time and neglect radiative cooling and heating of the gas[16,17].

These earlier studies have explored the effect of a single gas removal mechanism and are, at best, only qualitatively consistent with the current structure formation paradigm, a model with cold dark matter and a cosmological constant (ΛCDM). Recent attempts to study the evolution of dwarf satellites directly in cosmological simulations rely on semi-analytical methods to model the baryonic component rather than solving the fluid equations[18]. These models neglect ram pressure, and because stripping by tides is slow and inefficient, they cannot explain the complete absence of gas and early truncation of star formation of the darkest dwarf spheroidals.

In cold-dark-matter models the present-day spatial distribution of subhalos within primary halos retains some indication of their infall time[19]. Satellites orbiting closer to the primaries were on average accreted earlier than those orbiting at larger distances. Interestingly, Draco and Ursa Minor lie at 68 and 86 kpc , respectively, from the Milky Way, and Andromeda IX at 45 kpc from Andromeda, while other dwarf spheroidals orbit as far as 200 kpc from the primaries[1]. We use a high-resolution ΛCDM dark-matter-only cosmological simulation of the formation of a Milky-Way-sized halo[20] (see also Supplementary Information). At redshift $z = 0$ we identify three subhaloes having distances less than 100 kpc from the centre and with peak circular velocities in the range 25–30 km s^{-1} (ref. 6) (Fig. 1). We track the orbits of the satellites back in time and find that two of them were accreted early, between $z = 2.5$ and $z = 1.5$.

We then construct a high-resolution n-body + smoothed particle hydrodynamics model of a dwarf galaxy satellite having a disk of stars and gas inside a cold-dark-matter halo (Fig. 1) with a peak velocity of about 40 km s^{-1}, comparable to that of the two identified cosmological subhalos before they were accreted onto the Milky Way (see Supplementary Information). We assume that 80% of the baryonic disk mass is in a gas component. This inefficient conversion of gas into stars is expected at these low-mass scales because most of the gas will have densities below the threshold for star formation[21]. In addition, at $z > 2$ the gas in the dwarf is heated to a temperature of over 10^4 K and ionized by the cosmic ultraviolet radiation, which further suppresses star formation.

The dwarf model is placed on an eccentric orbit inside a massive Milky-Way-sized halo model which is a replica of that in the cosmological simulation. We include radiative cooling as well as the heating and ionizing flux from the cosmic ultraviolet background radiation[22], and we embed a diffuse gaseous halo inside the dark halo of the primary. Such a halo is expected as a by-product of the process of galaxy formation and has a density and temperature consistent with observational constraints (see Supplementary Information).

With an orbital time of about 1.7 Gyr, the dwarf undergoes as many as five pericentre passages in 10 Gyr. At the first pericentre passage its dark halo loses 60% of its mass. The disk, deep inside the potential well of the halo, suffers no stripping, but the tidal perturbation triggers a strong bar instability (Fig. 1) and simultaneously heats the stars in the disk. The bar funnels most of the gas towards the central kiloparsec. Gas will be removed from the galaxy if the ram pressure force exerted by the diffuse hot gas, which is proportional to $\rho_g V^2$ (ρ_g being the density of the gaseous halo and V being the orbital speed of the galaxy), exceeds the gravitational restoring force provided by the potential well of the galaxy[23]. Ram pressure readily removes the gas outside the bar

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radius on a timescale of less than 10^8 years, but not the more tightly bound gas inside the bar. When the satellite crosses the pericentre a second time, the new tidal shock lowers the halo density by a factor of two inside a kiloparsec, so that $V_{\rm peak}$ drops to less than $30\,{\rm km\,s^{-1}}$. The potential well has become shallower, so even the gas sitting inside the bar can be swept away by ram pressure (Fig. 1, see also Supplementary Information). The cosmic ultraviolet background heats and ionizes the gas, which enhances stripping significantly because the higher gas pressure opposes the gravitational restoring force. Once the first two orbits have been completed, no gas is retained by the dwarf.

The response of the system to the tides becomes progressively more impulsive at each new pericentre passage. As a result, the initially disk-like stellar distribution is heated into a nearly spherical, isotropic configuration (Fig. 1). The expansion reflects the attempt of the system to gain a new equilibrium as the internal binding energy is lowered. The removal of gas due to ram pressure is crucial for tidal heating to be effective (see Supplementary Information).

After ten billion years a diffuse spheroidal galaxy has replaced the gas-rich disk. During the last few orbits the stellar velocity dispersion profile is fairly flat (Fig. 2a), matching the profiles observed for Draco and Ursa Minor[24]. The initial angular momentum of the stars has been transported outward during the morphological transformation[8], producing a ratio between rotational velocity and the velocity dispersion (that is, the random motions) of $v_{\rm rot}/\sigma < 0.2$ in the inner few hundred parsecs. The surface brightness and total luminosity resemble those of the faintest dwarf spheroidals (see legend of Fig. 2a). A substantial halo is preserved within a few kiloparsecs from the centre so that the final M/L is larger than 100 (Fig. 2b). The central dark matter density, which has decreased by almost a factor of four since the beginning of the simulation, is $\sim 0.2\,M_e\,{\rm pc}^{-3}$, comparable to that of Draco and Ursa Minor[1].

We predict that all massive galaxies should have a few extremely dark-matter-dominated satellites as the mechanism reported here is completely general within hierarchical structure formation. The efficiency of star formation in isolated low-mass galaxies can be lower[21] than that assumed here (see Supplementary Information), and hence dwarf satellites having gas fractions higher than 80% of the baryons before stripping probably did exist. Once they lose their gas, these systems will turn into dwarf spheroidals even more dark-matter-dominated than Draco and Ursa Minor. They should orbit the Milky Way and M31 and have escaped detection so far owing to their low surface brightness, especially at low Galactic latitude[25]. Their halo masses should be comparable to those of known dwarf spheroidals and thus might help to solve the 'missing satellites problem'[26]. The Ursa Major dwarf recently detected by the Sloan Digital Sky survey[27,28], which has a halo as massive as that of Draco but a luminosity a hundred times smaller, is probably one of them. Three more systems such as Ursa Major would be enough to bring theory and observations into agreement at the high end of the mass function of satellites, corresponding to a peak circular velocity of around $25–30\,{\rm km\,s^{-1}}$, where suppression of baryonic infall by reionization is hardly effective.

When the ultraviolet background is an order of magnitude weaker, as is predicted[22] at $z < 1$, about 30% of the original gas component

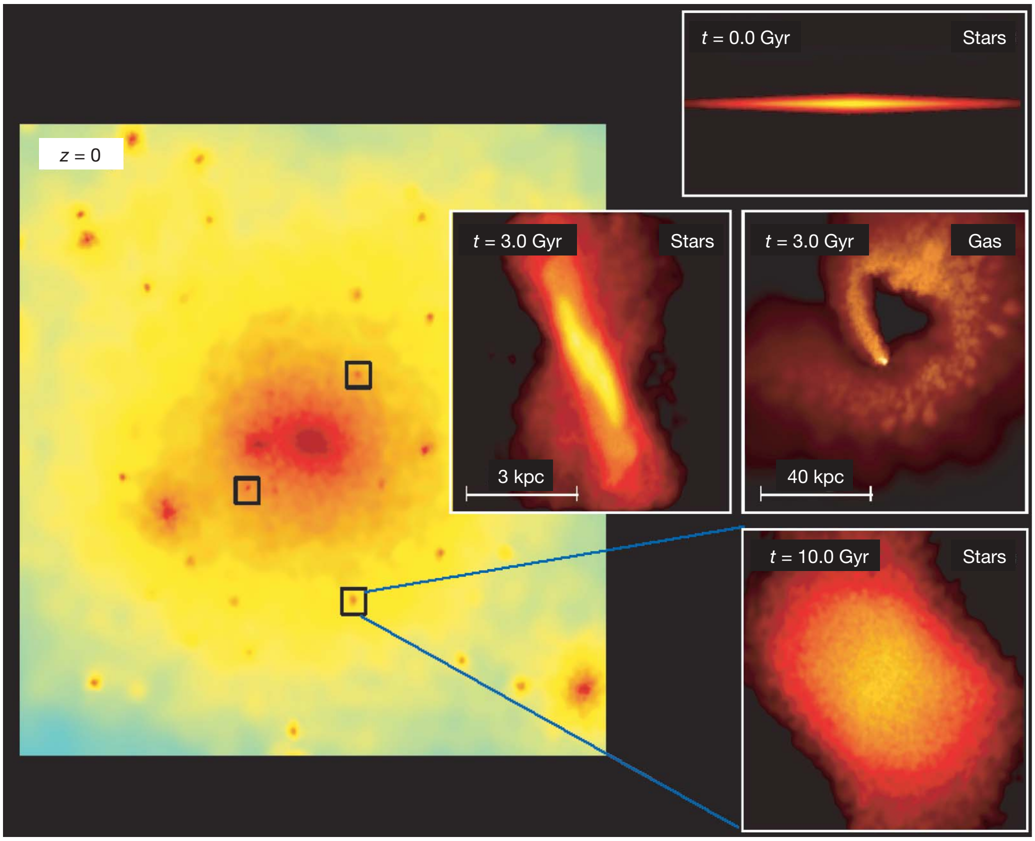

Figure 1 | Morphological evolution of the dwarf galaxy satellite. Colour-coded projected density map of the cosmological run at $z = 0$; the box is 260 kpc on a side, which corresponds to the virial radius of the Milky-Way-sized halo. The peak density along the line of sight is shown, ranging from $10^{-29}–10^{-24}\,{\rm g\,cm^{-3}}$, with the colour coding from blue (lowest density), through yellow, then red, to brown (highest density). The three satellites that meet the distance and circular velocity constraints (see text) are highlighted with black boxes. From top to bottom the insets show the stellar component of the dwarf galaxy, colour coded in projected density, at different times. Only regions with densities in the range $10^{-28}–10^{-23}\,{\rm g\,cm^{-3}}$ are shown, with the colour coding from dark red (lowest density) to yellow (highest densities). In the top inset, the initial disk is shown edge-on (the box is 8 kpc on a side). In the left middle inset, the system is close to the second pericentre passage; the stars have assumed a strong bar-like configuration and heating is evident in the outskirts (the box is 7 kpc on a side). In the bottom inset, the end state is shown; the bar has been heated into a diffuse spheroid and any disk-like feature has been erased (the box is 4 kpc on a side and a projection along a random line of sight is shown). In the right middle inset, the trail of gas produced by ram pressure is shown, while even the residual gas in the centre is stripped. The colour-coded gas density projected onto the orbital plane is shown (densities in the range $10^{-30}–10^{-23}\,{\rm g\,cm^{-3}}$, colour coding as above), and the box is 100 kpc on a side.

stays in the galaxy (see Supplementary Information). Therefore dwarfs that fell into the Milky Way halo late can continue forming stars, and tidal shocks will produce periodic bursts of star formation[10]. These newcomers should account for those dwarf spheroidals that have fairly normal mass-to-light ratios, extended star formation histories and larger distances from the primaries[1,2]. This explains why Fornax is ten times brighter than Draco and has a very different star formation history despite having a comparable depth of potential well[1,6,29]. It implies that there should be a positive correlation between M/L and the infall epoch of dwarfs, and thus a negative correlation between M/L and their orbital time. The dwarf spheroidal Tucana represents the biggest challenge to our model because it lies far from any massive galaxy (see Supplementary Information). The accurate determination of the orbits of the dwarfs expected from ongoing and future astrometric missions such as the Space Inteferometry Mission and the Global Astrometric Interferometer for Astrophysics will be able to test this prediction.

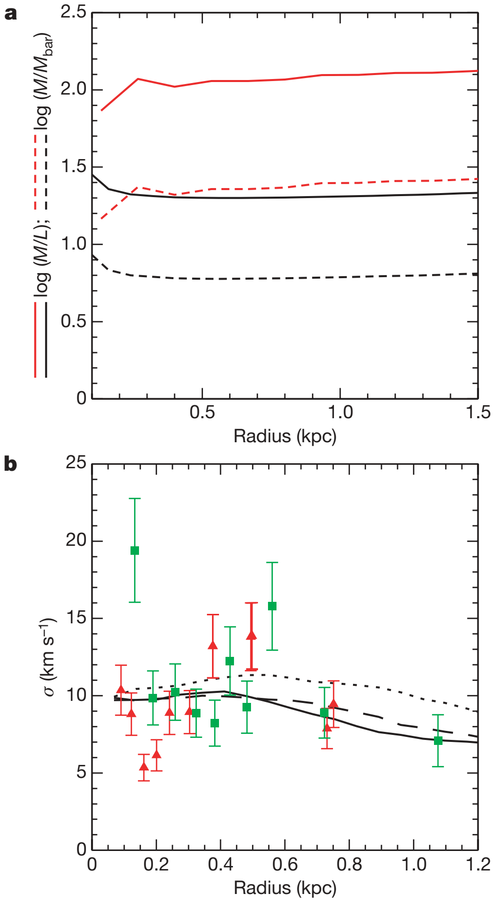

Figure 2 | Structural properties of the simulated dwarf after 10 billion years of evolution. a, Mass profiles shown out to the radius (from the centre of the simulated dwarf galaxy) at which stars are gravitationally bound. The dashed lines show the initial (black dashed line) and final (red dashed line) ratios of the total mass to the baryonic mass. The solid lines show the initial (black solid line) and final (red solid line) B band mass-to-light ratios of the dwarf. We have assumed stellar mass-to-light ratios of $M/L_{B*} = 1.5$ (initial) and $M/L_{B*} = 5$ (final) to compute the initial and final luminosities (as B band absolute magnitudes), $M_B = -12.5$ and $M_B = -9$. The final central surface brightness is $\mu_B \approx 26$ mag arcsec^{-2}. We note that using an initial $M/L_{B*} = 1.5$ is motivated by the fact that at $z > 2$ a stellar population is at most three billion years old, whereas a final $M/L_{B*} = 5$ is consistent with passive fading of the stellar population for about ten billion years[10]. **b,** The line-of-sight stellar velocity dispersion profiles are shown for three random directions (black lines) perpendicular to each other, together with published observational data points for Draco (red triangles) and Ursa Minor (green squares), including formal 1σ error bars[24]. The curves are shown out to the radius for which data points are available.

Received 11 July; accepted 22 December 2006.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank Y. Birinboim, A. Dekel, F. Governato, A. Kravtsov, G. Lake, C. Porciani, M. Valluri, B. Willman and A. Zentner, for discussions. We also thank S. Majewski and R. Munoz for sharing their data with us. L. Mayer and S. Kazantzidis are grateful to the Aspen Center for Physics, where some of this work was completed. All computations were performed on the Zbox supercomputer at the University of Zürich, on LeMieux at the Pittsburgh Supercomputing Center, and on the Gonzales cluster at ETH Zürich.

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