LETTERS

A common mass scale for satellite galaxies of the Milky Way

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The Milky Way has at least twenty-three known satellite galaxies that shine with luminosities ranging from about a thousand to a billion times that of the Sun. Half of these galaxies were discovered[1,2] in the past few years in the Sloan Digital Sky Survey, and they are among the least luminous galaxies in the known Universe. A determination of the mass of these galaxies provides a test of galaxy formation at the smallest scales[3,4] and probes the nature of the dark matter that dominates the mass density of the Universe[5]. Here we use new measurements of the velocities of the stars in these galaxies[6,7] to show that they are consistent with them having a common mass of about $10^7 M_\odot$ within their central 300 parsecs. This result demonstrates that the faintest of the Milky Way satellites are the most dark-matter-dominated galaxies known, and could be a hint of a new scale in galaxy formation or a characteristic scale for the clustering of dark matter.

Many independent lines of evidence strongly argue for the presence of dark matter in galaxies, in clusters of galaxies, and throughout the observable Universe[5]. Its identity, however, remains a mystery. The gravity of dark matter overwhelms that of the normal atoms and molecules and hence governs the formation and evolution of galaxies and large-scale structure[8–10]. In the currently favoured models of dark matter, structure in the Universe forms hierarchically, with smaller gravitationally bound clumps of dark matter—haloes—merging to form progressively larger objects.

The mass of the smallest dark matter halo is determined by the particle properties of dark matter. Dark matter candidates characterized as cold dark matter can form haloes that are many orders of magnitude smaller than the least luminous haloes that we infer from observations. Cosmological simulations of cold dark matter predict that galaxies like the Milky Way should be teeming with thousands of dark matter haloes with masses $\sim 10^6 M_\odot$, with a steadily increasing number as we go to the smallest masses[11–14]. A large class of dark matter candidates characterized as 'warm' would predict fewer of these small haloes[15]. However, even for cold dark matter it is uncertain what fraction of the small dark matter haloes should host visible galaxies, as the ability of gas to cool and form stars in small dark matter haloes depends on a variety of poorly understood physical processes[16–20].

The smallest known galaxies hosted by their own dark matter haloes are the dwarf spheroidal satellites of the Milky Way[3,4]. These objects have very little gas and no signs of recent star formation. The least luminous galaxies were recently discovered in the Sloan Digital Sky Survey (SDSS)[1,2] and follow-up observations have revealed them to be strongly dominated by dark matter[6,21,22].

We have compiled line-of-sight velocity measurements of individual stars in 18 of the 23 known dwarf galaxies in the Milky Way[6,7]. We use these measurements to determine the dynamical mass of their dark matter haloes using a maximum likelihood analysis[23]. The dynamical mass is best constrained within the stellar extent, which corresponds to an average radius of ~0.3 kiloparsecs (kpc) for all the satellites. We determine this mass, $M_{0.3}$, by marginalizing over a five-parameter density profile for dark matter that allows for both steep density cusps and flat cores in the central regions. It is important to note that the observed velocity dispersion of stars is determined by both the dynamical mass and the average anisotropy of the velocity dispersion (that is, difference between tangential and radial dispersion). The anisotropy is unknown and hence we marginalize over a three-parameter anisotropy function for stellar velocity that allows us to explore a range of orbital models for the stars[23].

Figure 1 shows the resulting determination of $M_{0.3}$. We find that all 18 dwarf galaxies are consistent with having a dynamical mass of 10^7 solar masses within 0.3 kpc of their centres, despite the fact that they have luminosity differences over four orders of magnitude. This result implies a central density for dark matter of $\sim 0.1 M_\odot\,\mathrm{pc}^{-3}$ in these galaxies. Earlier studies suggested that the highest luminosity dwarf galaxies all shared a common mass[4,24]. With larger stellar data sets, more than double the number of dwarf galaxies, and more detailed mass modelling, our results confirm this suggestion and conclusively establish that the dwarf galaxies of the Milky Way share a common mass scale.

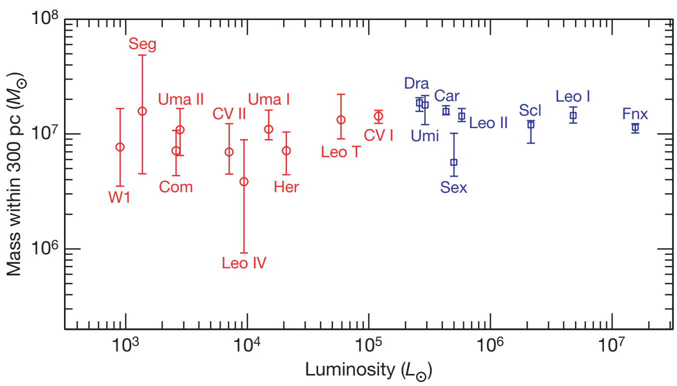

Figure 1 | The integrated mass of the Milky Way dwarf satellites, in units of solar masses, within their inner 0.3 kpc as a function of their total luminosity, in units of solar luminosities. The circle (red) points on the left refer to the newly discovered SDSS satellites, whereas the square (blue) points refer to the classical dwarf satellites discovered pre-SDSS. The error bars reflect the points where the likelihood function falls off to 60.6% of its peak value.

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Because of the proximity of the dwarf galaxies to the Milky Way, it is possible that tidal effects could change the velocities of stars and thus affect the mass measurements. In the kinematic data, tidal forces could be revealed as a velocity gradient across the observed plane of the dwarf[25,26]. We have tested the dwarf galaxies for velocity gradients and have found no conclusive evidence of tidal effects (see Supplementary Information).

We fitted a $M_{0.3}$-luminosity relation to these data and obtained $M_{0.3} \propto L^{0.03 \pm 0.03}$. This result does not change significantly if we use the luminosity contained within 0.3 kpc rather than the total luminosity. The common mass scale of $\sim 10^7 M_\odot$ may thus reflect either a plummeting efficiency for galaxy formation at this mass scale, or the fact that dark matter haloes with lower masses simply do not exist.

The characteristic density of $0.1 M_\odot\,\mathrm{pc}^{-3}$ may be associated with a characteristic halo formation time. In theories of hierarchical structure formation, the central density of dark matter haloes is proportional to the mean density of matter in the Universe when the halo formed. The earlier the formation, the higher the density. For cold dark matter models, our measurement implies that these haloes collapsed at a redshift greater than about 12, or earlier than 100 million years after the Big Bang. Measurements of the cosmic microwave background[27] suggest that the Universe went from being neutral to ionized at redshift 11 ± 1.4. These dark matter haloes thus formed at roughly the same time that the Universe was re-ionized.

Within the context of the cold dark matter theory, high-resolution cosmological simulations can be used to relate the mass within the central regions of the dark matter halo to the depth of the gravitational potential well[28]. Simulations show that $M_{0.3} \approx 10^7 M_\odot \times (M_{\mathrm{total}}/10^9 M_\odot)^{0.35}$, where M_{total} is the mass of the halo before it was accreted into the Milky Way host potential. Thus, it is possible that the implied total mass scale of $10^9 M_\odot$ reflects the characteristic scale at which supernova feedback[29] or the imprint of the re-ionization of the Universe[18,30] could sharply suppress star formation.

Perhaps a more speculative, but certainly no less compelling, explanation of the common mass scale is that dark matter haloes do not exist with $M_{0.3}$ below $\sim 10^7 M_\odot$. This implies that these dwarf galaxies inhabit the smallest dark matter haloes in the Universe. Warm dark matter has a larger free-streaming length than standard cold dark matter, which implies that density perturbations are erased below a characteristic length scale, resulting in a higher minimum mass for dark matter haloes. A thermal warm dark matter candidate with mass of about 1 keV would imply a minimum halo mass of $10^9 M_\odot$. Thus, our mass determinations rule out thermal warm dark matter candidates with masses less than about 1 keV, but dark matter masses somewhat larger than 1 keV would yield a minimum dark matter halo mass consistent with the mass scale we observe.

Future imaging surveys of stars in the Milky Way will provide a more complete census of low-luminosity Milky Way satellites, with the prospects of determining whether astrophysics or fundamental dark matter physics is responsible for setting the common mass scale. In particular, the masses for the faintest dwarf galaxies will become more strongly constrained with more line-of-sight velocity data. This will sharpen the observational picture of galaxy formation on these small scales and provide data around which theories of galaxy formation may be built.

Note added in proof: While this paper was in press, the luminosities of several newly discovered dwarf satellites were updated[31].

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

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