Our cosmic environment

The Milky Way's Neighbors

Dr. Ewa. L. Łokas studies the dynamics of the smallest and largest gravitationally bound objects that form the large-scale structure of the Universe: dwarf galaxies and galaxy clusters

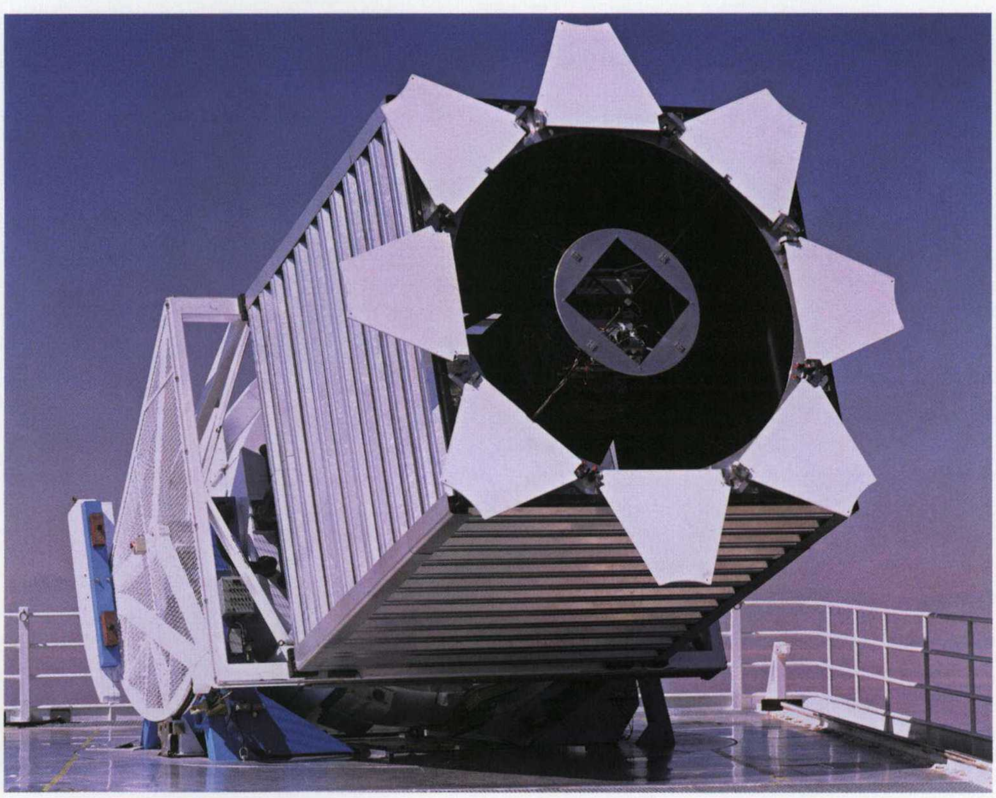
EWA L. ŁOKAS
Nicolaus Copernicus Astronomical Center, Warsaw
Polish Academy of Sciences
lokas@camk.edu.pl

Over the last two years the known population of dwarf galaxies in the neighborhood of the Milky Way - faint objects composed mainly of dark matter - has doubled. These new discoveries may contribute to solving one of the biggest riddles of modern cosmology: the problem of missing satellites

The largest telescopes presently enable us to observe galaxies which formed when the Universe was ten times younger, some of the first to be formed after the Big Bang. Yet there are still undiscovered galaxies within our own closest neighborhood, in the vicinity of the Milky Way. Over the last two years astronomers analyzing the results of the Sloan Digital Sky Survey (SDSS) have identified in the data previously unknown, very faint clusters of stars. The photometric properties of these objects (like the shape of the color-magnitude diagram for their member stars) allowed their distances and luminosities to be determined. The distances turned out to be rather small, on the order of 100 kiloparsecs (kpc), placing the objects inside our own Local Group of galaxies.

Local Group

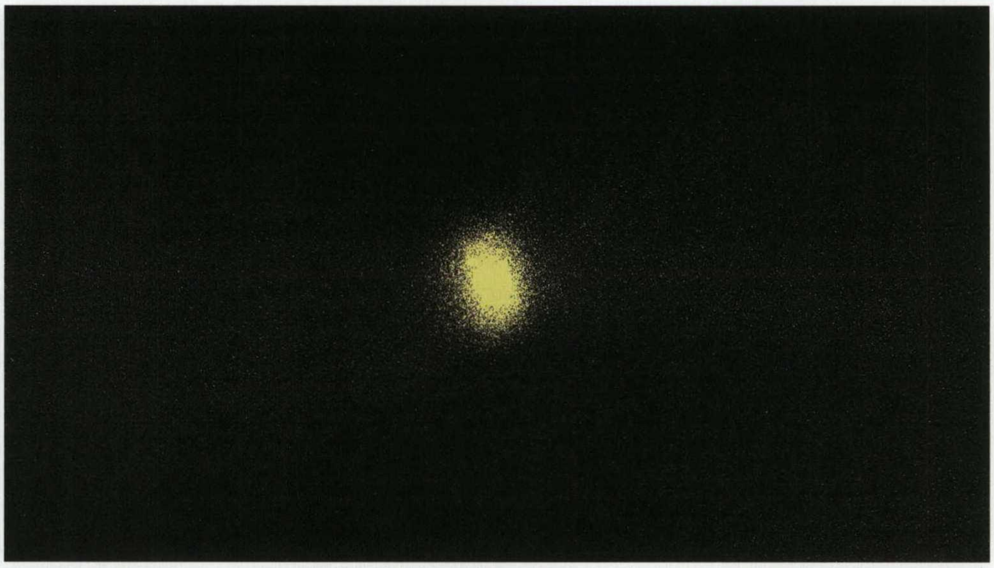
The Local Group is a relatively small group of galaxies, the Milky Way and Andromeda being its largest members. Each of these two is surrounded by a cloud of a dozen or so smaller dwarf galaxies orbiting their "hosts." The best studied objects of this type are the Magellanic Clouds, known to humans living in the Earth's southern hemi-



Fermilab Visual Media Services

The 2.5 meter telescope of the Sloan Digital Sky Survey (SDSS), used to discover the new dwarf galaxies

J. Klimentowski et al.



The final stage of the computer N-body simulation of a dwarf galaxy orbiting around the Milky Way. The galaxy lost 99 percent of its mass but it still forms a strongly gravitationally bound stellar system, almost spherical in shape. Visible at the opposite sides of the galaxy are the tidal arms formed as a result of the interaction with the Milky Way

sphere since antiquity. Apart from them the Milky Way is surrounded by nine other dwarfs discovered during the 20th century, all of them rather faint - otherwise they would have been found much earlier. The faintest have the luminosity of a hundred thousand suns, they are built of old stars, and their shapes bring to mind those of big elliptical galaxies, which is why they are often described as "spheroidal." The density of stars in them is nevertheless much lower than in classic elliptical galaxies, so that individual stars can be observed and their spectra even measured.

These measurements revealed a surprising property of dwarf spheroidal galaxies: they seem to contain much more of the so-called dark matter than the usual baryonic matter (such as stars, gas and dust), at a ratio even larger than in big galaxies like the Milky Way. This conclusion was based on analysis of the distribution of velocities of the stars measured from the spectra, which provides a measure of the galaxy mass. The velocities have a dispersion with respect to the mean velocity of the galaxy much too large for the stars to be gravitationally bound by the stellar mass alone. One particular example that is exceptionally dominated by dark matter can be found in the dwarf spheroidal galaxy in the constellation of Draco. Together with our collaborators we estimated the mass-to-light ratio in this galaxy to be 300 solar units, while it should not exceed a few units for a galaxy built of stars.

Another dwarf galaxy which we also modeled, in the constellation of Fornax, shows somewhat different properties. A certain amount (albeit much smaller) of dark matter is required to explain the measured velocity distribution here as well (the mass-to-light ratio is equal to 10). In addition, the distributions of stars and dark matter are similar, while in Draco the stars seem to be concentrated in the centre and surrounded by a much more extended dark matter halo.

Small galaxies

How do the newly discovered satellites compare to the old sample? They turn out to possess much lower luminosity, even down to a thousand suns. They also differ in shape - in most cases they are irregular, which may be due to the low number of stars or distortions due to interactions with the Milky Way. They seem, however, to be completely dominated by dark matter. Recent studies show that the mass-to-light ratio in some of them may be as high as 1000 solar units, although the estimates were performed for small stellar samples and still need to be confirmed.

The Milky Way's neighbors orbit around it and will eventually end up merging with their host. Such collisions cause the small galaxy to be completely swallowed and absorbed by the larger one, which remains little affected by the event. Such collisions have most probably happened frequently in the past, contributing to the growth of the

Our cosmic environment

Mischa Schirmer

The inconspicuous dwarf galaxy in the constellation of Draco is a gigantic concentration of dark matter - containing tens of times more dark matter than "ordinary" stars and gas

Milky Way's total mass. According to the widely accepted theory of the hierarchical structure formation in the Universe (from smaller to larger objects), small galaxies are the building blocks of larger ones. A present example of this phenomenon (occurring on the time scale of a billion years) can be found in the dwarf galaxy in the constellation of Sagittarius, which is currently being consumed by the Milky Way.

Cosmic interactions

Yet long before any such collision, the behavior of dwarf galaxies is already affected by presence of a big galaxy nearby. This impact can be of two kinds. First, the dwarf galaxy orbiting its host is influenced by strong tidal interactions trying to disrupt it. This is the same kind of interaction as the one which distorts the Moon and causes ocean tides on Earth. Its origin lies in differences between the gravitational attraction exerted by the bigger object on different (closer or more distant) parts of the smaller one. The interactions do not immediately lead to the disruption of the dwarf galaxy; it may remain on its orbit for billions of years while only losing stars and dark matter. The stripped matter forms characteristic tidal arms extending in opposite directions at two sides of the galaxy. Finally, the dwarf galaxy leaves behind a ring of stars surrounding the Milky Way. A few such streams have been discovered in the vicinity of our Galaxy and not all of them have been yet associated with their progenitor dwarf galaxies. These may be remnants of dwarfs swallowed by the Milky Way in the past.

According to simulations performed by our collaborators, over a period of 10 billion years a dwarf galaxy may lose 99 percent of its original mass, yet still remain a strongly gravitationally bound object that can be modeled by analyzing the velocity distribution of the stars. For some time astronomers considered the possibility that the large mass estimates (and thus also the inferred amounts of dark matter) could be due to perturbations caused by tidal interactions. Indeed, the stars in the tidal arms do not trace the gravitational potential of the dwarf galaxy any longer but still hover in its vicinity. We have shown, however, that after the stellar samples are properly cleaned the mass estimates are reliable.

The second effect caused by the presence of a big galaxy manifests itself in changes in the dwarf galaxy's shape. It is generally believed that all galaxies started their life as spirals or disks, because gravitational collapse of any object leads to concentrated angular momentum and accelerated rotation. So how did elliptical galaxies form? The big objects of this type probably formed as a result of mergers between two or more spiral galaxies with randomly oriented angular momenta. The ordered rotational motion is then transformed into random motions of the stars in different directions. Simulations show that in the case of dwarf galaxies the dominant role may be played by tidal interactions, which transform disks first into elongated bars and then into spheroidal objects.

One interesting example illustrating both these effects of tidal interactions is the dwarf spheroidal galaxy Leo I, which we recently studied. Located at as far away as 250 kpc, it is one of the Milky Way's more distant satellites and is receding from us at significant speed so that it is not clear at all whether it is gravitationally bound to our Galaxy. According to the scenario presented above, if spheroidal galaxies formed out of disks they may possess some residual rotation - weak rotational motion as an addition to the random motion of the stars. Such rotation was indeed successfully observed, but surprisingly the nucleus of the galaxy seems to rotate in the opposite direction compared to the outer parts. This effect can be explained by the presence of tidal arms oriented almost exactly along the line of sight. Away from the centre of the galaxy the outflow of matter in the arms dominates over the internal rotation, causing its apparent reversal.

Problem of missing satellites

Computer simulations of the evolution of the dark matter distribution and the formation of galaxy groups like our Local Group performed within the standard cosmological model lead to the conclusion that we should find not a few tens but rather a few hundred dwarf galaxies in our nearest neighborhood. This discrepancy has come to be known as "the problem of missing satellites." So, is the theory of structure formation on which the simulations are based incorrect, or have we not yet discovered all the neighbors of the Milky Way? Or perhaps they do exist as gravitationally bound objects but are composed almost exclusively of dark matter, i.e. for some reasons they did not form stars? In view of the recent discoveries of the new satellites, it seems that these latter possibilities are more probable. The recently discovered objects do not yet solve the problem because they barely double the Milky Way's number of neighbors. It should be kept in mind, however, that SDSS has so far covered only part of the sky so new discoveries are certainly in store for us. ■

Further reading:

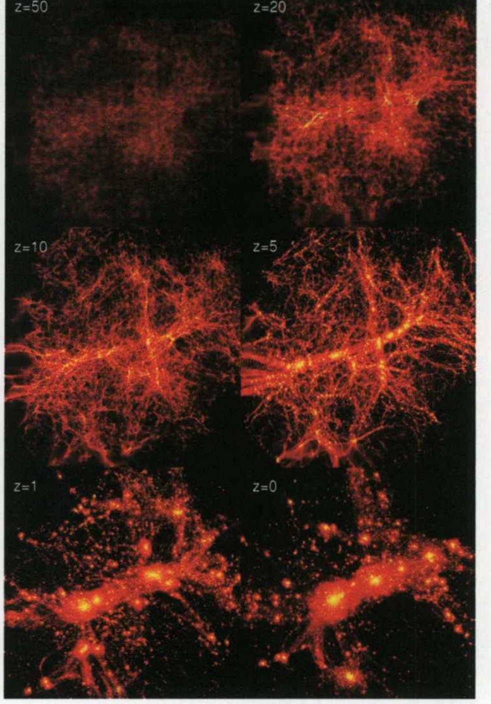
Belokurov V., et al. (2007). Cats and dogs, hair and a hero: a quintet of new Milky Way companions. *ApJ, 654*, 897; http://arxiv.org/abs/astro-ph/0608448

Klimentowski J., Łokas E.L., Kazantzidis S., Prada F., Mayer L., Mamon G.A. (2007). Mass modelling of dwarf spheroidal galaxies: the effect of unbound stars from tidal tails and the Milky Way. *MNRAS, 378*, 353; http://arxiv.org/abs/astro-ph/0611296

Łokas E.L., Mamon G.A., Prada F. (2005). Dark matter distribution in the Draco dwarf from velocity moments. *MNRAS, 363*, 918; http://xxx.lanl.gov/abs/astro-ph/0411694

Mayer L., Governato F., Colpi M., Moore B., Quinn T., Wadsley J., Stadel J., Lake G. (2001). The metamorphosis of tidally stirred dwarf galaxies. *ApJ, 559*, 754; http://arxiv.org/abs/astro-ph/0103430

Ben Moore



Our Local Group of galaxies is composed of two big objects, the Milky Way and the Andromeda galaxy, as well as a few dozen dwarf galaxies. Cosmological simulations (illustrated here), however, predict that the number of dwarf galaxies should be about ten times larger