Dark Matter on small scales; Telescopes on large scales

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Abstract

This article reviews recent progress in observational determination of the properties of dark matter on small astrophysical scales, and progress towards the European Extremely Large Telescope. Current results suggest some surprises: the central DM density profile is typically cored, not cusped, with scale sizes never less than a few hundred pc; the central densities are typically $10^{-20}$ GeV/cc; no galaxy is found with a dark mass halo less massive than $\sim 5 \times 10^7 M_{\odot}$. We are discovering many more dSphs, which we are analysing to test the generality of these results. The European Extremely Large Telescope Design Study is going forward well, supported by an outstanding scientific case, and founded on detailed industrial studies of the technological requirements.

1 Dark Matter on small scales

Are dSph haloes cusped or cored? Debate continues to rage about whether the cusped haloes always created in CDM simulations are in conflict with observations of rotation curves of Low Surface Brightness galaxies. The gas-free nature of dSphs makes them kinematically clean systems in which to test theoretical predictions. Stellar velocities may also be used to place constraints on the steepness of any possible central cusp, whether due to a black hole, the intrinsic physical properties of the CDM, or possibly even CDM as modified by a central black hole.

In the last few years several groups have obtained large kinematic data sets, determining the line-of-sight velocity dispersion across the face of many of the local dSph galaxies. These data, together with surface brightness profiles defining the scale length on which the light is distributed, allow standard stellar velocity pressure vs gravitational pressure gradient analyses through application of the Collisionless Boltzmann equation, or more commonly the moment equations known as Jeans’ equations.

As a general result, in all cases with sufficient data we rule out (King model) mass-follows-light models. King models are not an adequate description of these galaxies, all of which have high mass-to-light ratios (in solar visual band units), and extended dark matter halos. Even in the inner regions mass does not follow light, while including outer data commonly we find a most likely global mass to light ratio which is very high, being for Draco $\sim 440$, 200 times greater than that for stars with a normal mass function (Fig. 1). The Draco halo models favoured by the data contain significant amounts of mass at large radii, leading to the observed flat to rising velocity dispersion profiles at intermediate to large radii.

Figure 1 summarises Jeans equation models for several of the dSph, with in each case the simplest possible assumptions (isotropic radially-constant velocity distribution). It is apparent that the models are invalid at large radii, where an unphysical oscillation in the mass profiles is evident. In the inner regions however the fit to the data is good. In each case, a core-like mass distribution is preferred. The well-known and irreducible feature of
moment analyses applied to a collisionless system, when there is no equation of state to relate pressure and density, however, means it is possible, by adding a radially-variable stellar anisotropy (essentially an extra stress function) to the fit, to fit steeper cusp-like central mass distributions.

The profiles in figure 1, derived by Jeans’ equation analyses, and the correlation in figure 2, when taken together, illustrate two of our basic results. In every case, the simplest analysis favours cored mass distributions. While cusped mass distribution can usually be fit to the data, in at least one case, UMi, there is very strong direct evidence that a cusp model is inadequate to explain all the available information. The conservative assumption is therefore that all the mass profiles are indeed cored, and are significantly shallower than $r^{-1}$.

Secondly, all the dSph we have analysed to date show very similar, and perhaps surprisingly low, central dark matter mass densities, with a maximum value of $\sim 5 \times 10^8 M_\odot kpc^{-3}$, equivalent to $\sim 20$GeV/cc. Interestingly, the rank ordering of the central densities is in inverse proportion to system total luminosity, with the least luminous galaxies being the most dense. This is of the opposite sign to some CDM predictions.

It is apparent from Figure 2 that there is remarkably little spread in mass within the optical boundary apparent among the galaxies with absolute magnitude fainter than $\sim -11$. This relation was considered until recently to be a minor curiosity, since it covered the dynamic range only from $M_V \sim -13$ to $-9$, a mere factor of forty or so in luminosity, and included only 8 galaxies. However, the recent analysis of the newly-discovered extremely low luminosity dSph galaxy UMa has extended the validity of the relation by another two magnitudes, now a factor of $\sim 200$ in luminosity, and to total mass-to-light ratios in excess of 1000.

The results of figures 1 and 2 are explicable if there is an intrinsic minimum scale length - about 100pc - an intrinsic maximum central mass density - about $10^{-20}$GeV/cm$^3$ - and a similar universal mass profile. The total mass, simply the product of these, is then naturally constant. These results are described and discussed further in Gilmore et al (2007).

Several other new very low luminosity dSph satellite galaxy candidates have been discovered in the last few months, while new studies of several known galaxies have recently been completed. It will be very interesting to see if these dynamical studies strengthen or disprove this apparent trend.

2 The European Extremely Large Telescope

Several teams worldwide have begun development of the next generation of Extremely Large ground-based Telescopes (ELTs). A range of designs and telescope sizes from 25-45m are being considered, with the larger apertures under study in Europe.

In writing the science case for an ELT, we are in an unusually advantageous position. The present generation of ground-based telescopes, complemented by HST and other satellites, have revolutionised our view of the Universe, illustrating the power of large telescopes through performance, and have produced a wealth of fascinating questions that only the vast collecting area and high spatial resolution of an ELT will be able to answer. These questions cover areas across planetary science, astronomy and cosmology. They range from long-term modeling of weather patterns in Solar System planets, through direct imaging of Earth-like bodies around other stars, to understanding the complete formation histories of galaxies, particularly including the first objects, the role of reionisation, and the development of dark-matter structures.

Cutting-edge telescopes are immensely flexible tools that can be turned to many different projects. This flexibility means that some of the most exciting discoveries will be those that one cannot predict before the instrument is built. Thus, for example, the majority of the science highlights of the first ten years of the Keck telescopes’ operations – such as their part in the distant supernova observations that led to the discovery of dark energy – were not featured in the list of science objectives prior to the telescopes’ construction. However, even as written, the science case for an ELT is spectacular. Not only will it allow us to address a wide range of already-posed key scientific questions, but it will also provide the complementary data that will unlock the full potential of facilities at other wavelengths,
Figure 1: Derived inner mass distributions from Jeans’ eqn analyses for four dSph galaxies. Also shown is a predicted $r^{-1}$ density profile. The modelling is reliable in each case out to radii of $\log (r)_{\text{kpc}} \sim 0.5$. The unphysical behaviour at larger radii is explained in the text. The general similarity of the four inner mass profiles is striking, in all of shape, length scale and normalisation. This figure is from Gilmore et al (2006).

Figure 2: The Mateo plot (cf Mateo 1998): Mass to light ratios vs galaxy absolute V magnitude for some Local Group dSph galaxies. The solid curve shows the relation expected if all the dSph galaxies contain about $4 \times 10^7$ solar masses of dark matter interior to their optical radii. This figure is from Gilmore et al (2006).
Figure 3: An outline design for a 42-m E-ELT, as of late 2006. Optimisation and development continue through ESO, national agency, and EC, funded projects.
especialy JWST.

The ELT will allow study of planets orbiting other stars – direct detection of extrasolar planets and a first search for bio-markers (e.g. water and oxygen) in nearby systems may be feasible with an ELT. Mapping orbits of gas giants, determining their composition, albedos and temperatures will be a first step on the way to the more challenging exo-earth observations. Detailed analysis of the formation of planetary systems and protoplanetary disks in nearby star-forming regions will also become possible.

Resolved stellar populations studies will extend from studies of individual stars so far possible only in our Galaxy and its satellites to a representative section of the Universe, reaching (with the largest ELTs) the Virgo cluster of galaxies. This will provide information on how galaxies form, as the ages and compositions of stars reflect past histories. Massive Black Hole demography will be extended through dynamical analysis of circum-nuclear regions of galaxies, to establish whether properties seen in AGN hold also for dwarf galaxies, mapping Black Hole formation and evolution across a wide mass-range. Star formation histories across the Universe will be quantified: when did the stars form? Using the fact that high-mass stars soon die in supernova explosions, it is possible to deduce the number of stars that have formed at each redshift, tracing star formation back to re-ionization.

The dynamics and kinematics of galaxies and their sub-galactic satellites within large dark matter haloes can be traced with an ELT out to redshifts of about 5. Thus we can observe the build-up of such dark-matter structures in the process of formation. Similar supernova observations to those used to determine the star formation history will be used to probe on empirical grounds cosmological models for the nature of dark energy out to the earliest epochs. A first generation of objects providing the necessary UV photons to re-ionize the hydrogen in the Universe must have existed. An ELT will distinguish between candidates: QSOs, primordial stars, SNe. The brightest earliest sources (GRBs, SNe, QSOs) are ideal to probe the high redshift interstellar and intergalactic medium.

In some science cases there is a continuum of improvement as telescope diameter increases, but there are also a few important critical points where a telescope above a certain size enables a whole new branch of study. Three key scientific drivers are used to optimise the science return as a function of aperture. These are (1) detection and study of extra-solar planets (2) study of galaxy formation via observations of resolved stellar populations, quantifying the role of dark matter and (3) the early universe and the first objects, quantifying the role of dark energy.

We already know that the up-coming generation of space observatories (such as Herschel and XEUS) operating at wavelengths from the far infrared to X-rays, will need the kind of complementary data that only an ELT can provide. The synergy between ground and space-based observations in the optical and near-IR has been clearly demonstrated by projects at the forefront of research which required the combination of HST and current 8-10m telescopes in order to make their discoveries: for example the study of distant supernovae and the discovery and follow-up of Lyman-break galaxies both make use of HST for imaging, and large telescopes for spectroscopy. For many observations a telescope’s ability to detect faint sources scales as $D^2$ and the time to carry out a given observation scales inversely as $D^4$ (where $D$ is the primary mirror diameter). Their great aperture means that ELTs are able to compete with space-based telescopes despite the reduced background in orbit. For high-resolution spectroscopic applications, ground-based ELTs can compare in performance with, or significantly out-perform, the (e.g.) JWST in the transparent atmospheric windows out to at least 4microns. Even in imaging mode, ELTs larger than 20m compare in performance to JWST at all wavelengths shorter than 2.5micron. Already images from HST’s Advanced Camera for Surveys reveal objects that are too faint for the largest existing telescopes to obtain spectra. The advent of the JWST, scheduled for launch in 2013, will only serve to increase the opportunity.

The various European projects (EURO-50, OWL) have been brought together into a single European project, led by and largely funded through ESO, with significant national and EC support. Figure 3 illustrates the current 42-m aperture default design. Project updates can be found at www.eso.org/projects.
3 References

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