Dark Matter

Yorck Ramachers
Oxford University, NAPL, Keble Road, OX1 3RH, UK

Dark matter is among the hottest topics of research in astrophysics. Although the phenomenon has been noticed the first time almost seventy years ago by F. Zwicky, in recent times dark matter research entered a new era. Its existence is practically accepted due to independent and converging observations in astrophysics (see also the articles in this special issue by J.M. Lamarre and J.L. Puget and by P.D. Sackett). However, the actual composition of dark matter is yet to be determined.

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Dark matter as a puzzle inspires astrophysicists and particle physicists, amalgamating these research areas into the rather young discipline of astroparticle physics. To summarize roughly the present status, the overwhelming majority of mass in the universe neither emits nor absorbs light and nobody knows what it is made of. The exercise is clear: to reveal the nature of dark matter and its role in the universe.

Mass and energy budget of the Universe

Fig. 1 shows the mass and energy budget of the universe as known today. Two dark matter problems can be found there (labeled gap I and II).

1. there are dark baryons (gap I), hence missing normal matter. So far, astronomers did not find all the normal matter that should exist in the universe due to the very successful theory of primordial nucleosynthesis.
2. There has to be a non-baryonic dark matter contribution (gap II). The observations today agree on a universe matter content of about 35% of the critical density (the mean matter density to have a flat universe) on average. The maximum allowed amount of baryonic matter, however, is just about 5%. This discrepancy leads to the notion of non-baryonic dark matter – the small syllable 'non' has far-reaching consequences.

Non-baryonic is synonymous with an exotic form of matter that we do not know. It is therefore a main playground for particle physicists entering the field of dark matter. A more detailed presentation of Fig. 1 and the terms used there will be given below.

The main motivation for current experiments to reveal the nature of dark matter or at least some specific properties different than just mass can be understood from Fig. 2. The idea is that all luminous matter is embedded in a huge halo of dark matter. Shown in the right panel one can find the basis for such a model: measurements of the rotation velocity of test bodies (stars, gas clouds) around the center of a galaxy yield its rotation curve. As indicated in the right panel, our galaxy has an approximately flat rotation curve, inconsistent with the expected Keplerian decline (dotted curve) in case all the mass was luminous (velocity $\propto 1/\sqrt{(\text{distance to center})}$). Instead, a constant rotation velocity implies a linearly increasing galaxy mass distribution and in fact this has been measured (left panel) up to very large distances of about 200 kpc (our sun is located at the outskirts of the Milky Way galaxy at a radius of about 8 kpc).

Baryonic or exotic?

These observations motivate us on Earth to search for dark matter either in our local (galactic) neighbourhood or even in laboratory experiments. Plenty of candidates for dark matter have been proposed. They can be classified as baryonic and exotic (or non-baryonic).

This distinction is crucial with respect to the two dark matter (DM) problems of Fig. 1. Baryonic candidates can at best fill gap I. These candidates consist of gas, planetary objects and stellar remnants, for example white dwarfs. They would be too dim to be observed with telescopes and therefore would be dark matter by definition. However, the clever idea of microlensing can help to detect such candidates and has been successfully applied.

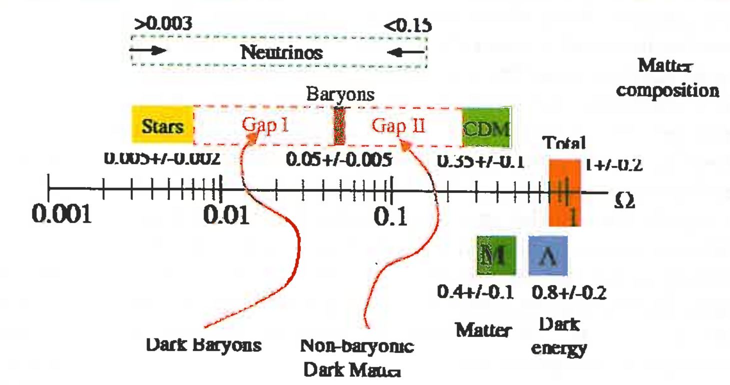

Fig. 1: Mean matter/energy density in the universe normalised to the critical density. A value of Ω=1 means a flat universe topology as the boundary case between a spherical and hyperbolic topology (for simple cosmologies this means closed and open universe). Summaries of measurements for this important parameter are indicated. Below the logarithmic axis is shown an overall account of matter and energy; above the composition of the matter components. The dotted red rectangles, labeled gap I and II indicate the two dark matter problems: dark baryons and non-baryonic dark matter. Colored regions: yellow – range of luminous matter, brown – required range of baryonic matter due to primordial nucleosynthesis, light green – range of non-baryonic cold dark matter (CDM), red – total account of matter/energy density consistent with Ω=1, dark green – total matter content in the universe, blue – dark energy content adding up with matter to the total content. The dashed green rectangle shows the allowed amount of matter density due to neutrinos. Lower bound due to successful neutrino mass measurements, upper bound from failure of structure formation scenarios using neutrinos as hot dark matter. The picture has been adopted from M.S. Turner's dark matter review in Phys. Reports (see references).

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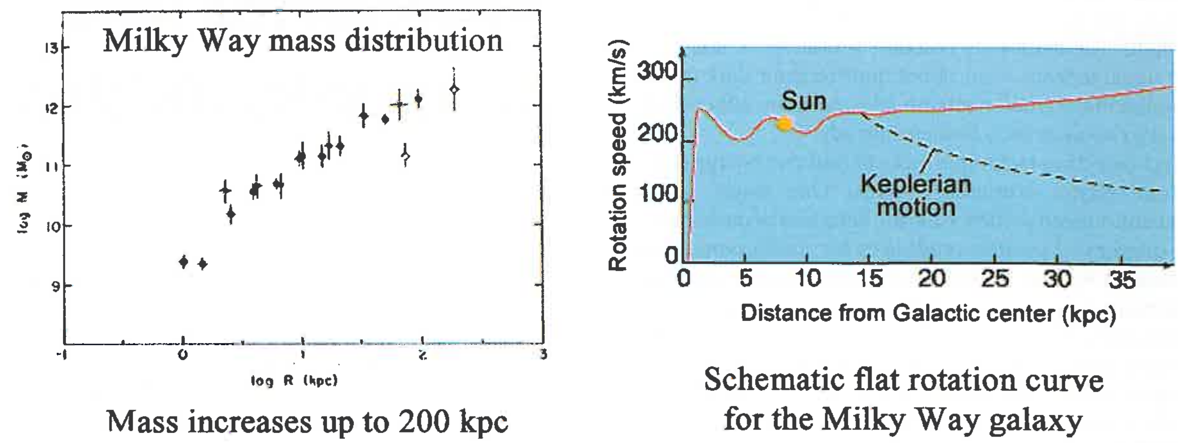

Fig. 2: The right panel shows a schematical rotation curve of our galaxy (from http://www.astro.psu.edu/users/niel/psiwa/darkmatter/mw-rotation-curve.jpg, on Penn State Inservice Workshops in Astronomy). The important observation is that the velocities of stars and gas spinning around the center of the galaxy remains constant up to the largest measured distances. If nothing else but luminous matter was there, the rotation curve should decrease as indicated (dashed line). Therefore there must be much more mass inside and around our galaxy than visible, the dark foundation. In fact, the flat rotation curve implies a linear increase of the total mass with increasing distance from the center. That has been observed as is shown in the left panel up to large distances (from S.M Faber and J.S. Gallagher, Ann. Rev. Astron. Astrophys. 17 (1979) 135, or http://ned.ipac.caltech.edu/level5/Faber/Faber_contents.html).

This technique looks for light amplification of distant stars of the two Magellanic Clouds by massive compact halo objects (MACHOs) from our Milky Way galaxy. This amplification is a generic effect of the gravity field of the MACHO that bends the light and eventually acts as a lens (see also P.D. Sackett's article) for an observer on Earth. The probability that a given star is amplified at a given time is very low; millions of stars have to be monitored for years in order to ever be able to detect such a rare event. The MACHO and the EROS (Expérience pour la Recherche d'Objets Sombres) collaboration have indeed found microlensing events but their interpretation poses some considerable problems. They are consistent with a roughly 50% dark baryon halo but the masses of the lenses needs to be around half a sun mass which would mean they are probably white dwarfs. That turns out to be inconsistent with several astronomical observations, so the latest status is that the nature of the lenses is unknown. Nevertheless, something has caused these microlensing effects and it remains a fascinating challenge to explain them.

Hot and cold non-baryonic dark matter

Non-baryonic candidates are classified as hot and cold DM (also an intermediate state, called warm DM has been proposed), depending on their kinematical state in the early universe at the time of decoupling of light and matter. Hot DM candidates would have been relativistic, cold DM ones non-relativistic. The reason for such a classification originates from the fundamentally different consequences for structure formation in the universe, like formation of superclusters and clusters of galaxies. Hot DM would form huge structures first (top-down approach), cold DM vice versa. The important efforts of research groups using supercomputers for N-body simulations of huge parts of the universe showed that structure formation cannot be understood with dominantly hot DM. A consistent scenario results for a substantial cold DM component and a rather negligible hot DM component.

However, it also turned out that realistic scenarios for structure formation need one mysterious part in addition to cold DM: dark energy. The nature of dark energy is unknown but it can be described as a smooth component which contributes at least 60% of the energy density in the universe (see Fig. 1). It must evolve more slowly than matter not to interfere with structure formation at early times. In addition, it has to have a negative pressure! In order to explain recent cosmological observations (see also J.M. Lamarre and J.L. Puget's article), especially the distant supernova Ia surveys, the universe accelerates instead of slowing down or keeping a constant expansion rate. Initially, this observation led to a revival of Einstein's cosmological constant but soon it has been realized that also time dependent variants, termed quintessence, could explain the dark energy. No conclusion can be given so far about the dark energy but huge efforts are underway to measure the equation-of-state of this phenomenon in order to learn about its nature.

Search techniques

The prime candidate for a hot DM contribution is a massive neutrino. The new results from the Superkamiokande experiment and recently from SNO (Sudbury Neutrino Observatory) seem to prove for the first time that neutrinos are in fact massive although extremely light. Their possible contribution to dark matter is summarised in Fig. 1 as well. Nevertheless, they will not be able to fill exotic matter gap II.

Searches for non-baryonic, cold dark matter exist in a large variety of techniques. One can classify them as three different concepts: production in laboratory experiments (typically at accelerators), indirect and direct detection. These techniques presume that this exotic form of matter consists of unknown particles.

Indirect searches look for products of reactions of these particles. It might be that they decay or annihilate or have inelastic reactions with normal matter, meaning that they might not be 'dark' in the strict sense but shine in 'some' form. Satellite experiments look for radiation from such reactions, for example in the form of high energy gamma rays or antiprotons. Additionally, neutrino 'light' (neutrinos as reaction products) is seen as a promising signal to learn more about non-baryonic dark matter. Large experiments, termed neutrino telescopes, are either in the process to start soon or even measure already.

The direct detection technique seeks to find rare energy depositions from elastic scattering events. One direct search experiment announced evidence for the detection of dark matter. The main category of particle candidates for non-baryonic dark matter are called WIMPs (weakly interacting massive particles). One important signature of WIMP interactions would be an annual modulation of these rare events. The DAMA collaboration, operating almost 100 kg of low background NaI scintillator detectors in the Gran Sasso laboratory in Italy has published evidence for the detection of such a modulation, consistent with the WIMP hypothesis. Now other experiments are bound to confirm or exclude that evidence which promoted large efforts and interest worldwide in inventing alternative and far more sensitive detectors. That compelling development happens at the moment and new results are expected very soon.

To conclude, dark matter appears to be well established as a phenomenon in astrophysics, a fascinating puzzle. Precision cosmological measurements determine the matter and energy content of our universe and reveal the necessity for a substantial amount of unknown matter, a dark side of the universe. Astronomical techniques like supernova searches seem to have detected dark energy, an unexplained phenomenon so far, hinting at new physics beyond current borders. About matter in the universe, we now have a clear picture that the familiar luminous matter represents only a negligible contribution with respect to dark matter. Normal, known forms of matter evaded detection so far and so did an even larger contribution from an exotic form of dark matter. The near future will most probably reveal some pieces of the grand mosaic and it's exciting to follow that development.

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About the author

Yorck Ramachers has been a research assistant at Oxford University since 1998, working for the direct detection experiment CRESST (cryogenic rare event search using superconducting thermometers) at the Gran Sasso laboratory in Italy in the group of Prof. H. Kraus.
PhD. thesis 1998 at the Max-Planck Institute for Nuclear Physics in Heidelberg on building the HDMS (Heidelberg dark matter search) direct detection experiment in the group of Prof. H.V. Klapdor-Kleingrothaus.