Dark Matter

Introduction

Until now, matter in the universe resembles the case of an iceberg – the largest part remains hidden. The objective fact that the combined mass of all observed celestial bodies barely represents a tiny fraction of the "grand total", both surprises the layman and concerns the scientist. The 'dark matter' issue arguably becomes one of the biggest unsolved problems in nowadays astrophysics.

Dark mater becomes a large multidisciplinary issue, as it is highly interconnected with many and varied topics, from particle physics to cosmology and full-band observational astronomy, from stellar astrophysics to classic dynamics and relativistic gravity. Hopefully, its definite solution now appears quite accessible.

Why there has to be some dark matter at all, what stuff that dark matter could be, which of the many dark matter candidates are the most probable ones, and which experiments are currently being performed in order to unquestionably identify it, are the four major questions that will guide the development of this report.

What's the 'dark matter issue' all about?

The "mystery" about dark matter basically refers to the notorious discrepancy between how mass is actually moving at large scales in the universe – large enough to embrace a whole galaxy – and the way it should be moving according to its so far verified existence. Either our gravity laws do not apply at such large scales, or there are huge amounts of mass hidden from our contemporary detection capabilities. No further explanations could apply.

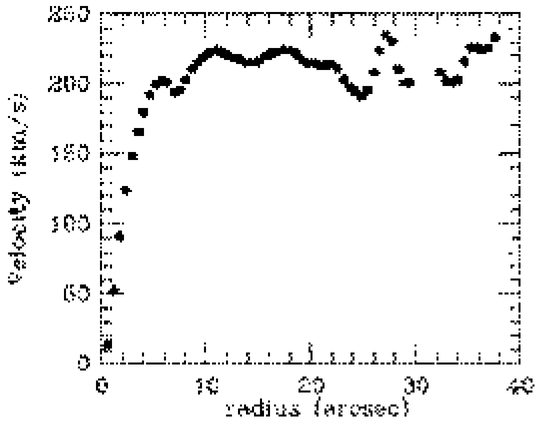

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Figure 1
Milky Way's rotation curve

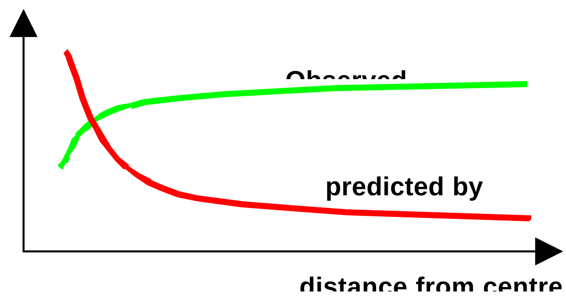

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Figure 2
Generic galaxy rotation curve

Two illustrative examples supporting the mass deficiency case are:

(a) *The measured uniform orbital speeds in the outer parts of disk galaxies*. Figure 1 shows the particular curve of Milky Way's rotation, but most spiral galaxies have been found to revolve with a similar profile – as the radius increases, the orbital speed flattens out. The stylized graph in Figure 2 compares actual velocities to what would correspond according to detected mass. Not only the detected mass is less than required, but mostly surprising, nothing but about 10 % of what it should be ***[1]***.

(b) *The mere existence of galaxy clusters*. In order to preserve rich galaxy clusters hold together, like the Coma cluster showed in Figure 3, strong gravitational forces have to prevent galaxies from flying apart. Computations demonstrate that the required mass to bind such a galaxy cluster is about 10 times more than all the mass so far detected, even considering the huge amounts contained in the intracluster gas (which even per se usually overcomes the combined mass of all the stars in all the cluster's galaxies) ***[2]***.

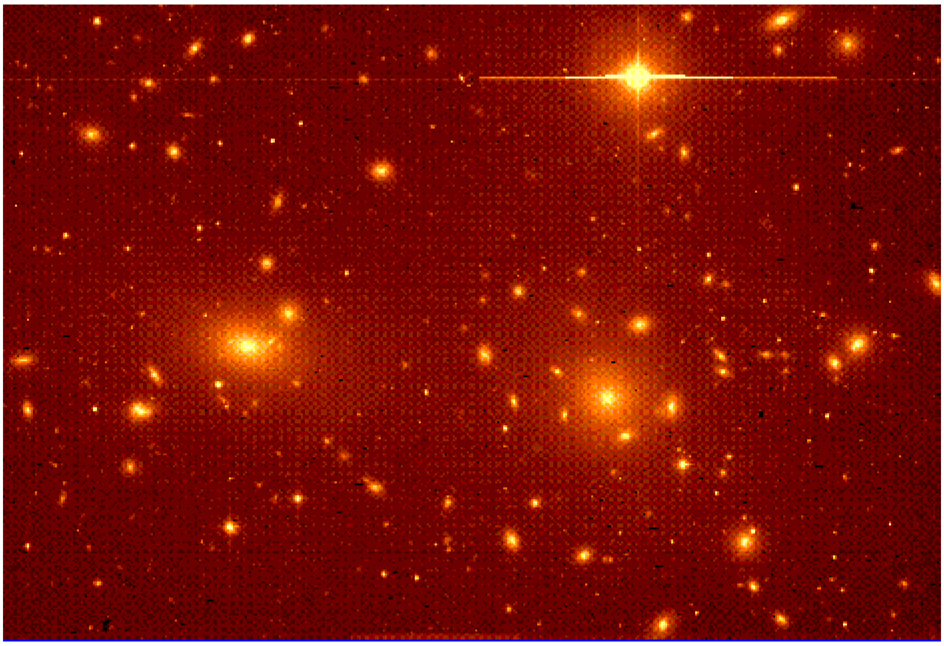

Image by Gregory Bothun (University of Oregon)

Figure 3
A typical rich cluster of galaxies: the Coma cluster. It contains over a thousand member galaxies known. Most of the objects in this picture are galaxies; only the very bright objects with diffraction spikes and the smallest circular dots are foreground stars in our Galaxy.

So far, Newtonian laws have been unquestionably verified up to around 50 AU[1]. However, whether or not for large scales gravity still varies exactly as the inverse of the squared distance remains objectively unknown. Alternative theories with different relationships have been proposed, collectively named as 'MOND' – for *Modified Newtonian Dynamics*. Although some have conciliated very well (new) theory with observations, the major problem – also explaining their low general acceptance – is to make them consistent with General

[1] Up to where robotic spaceships so far have traveled furthest (a tiny distance at the Solar System scale).

Relativity. Anyway, although improbable, if MOND happens to be right, the whole dark matter affair falls down like a card castle ***[3,4]***.

Having accepted the everywhere full validity of Newtonian laws, the remaining possibility for the missing matter is to consider that some real material objects have yet evaded been observed by state-of-the-art radio, infrared, optical, ultraviolet, X-ray, and gamma-ray telescopes, both from ground and space. Any veritable dark matter candidate has to simultaneously comply:

(a) it doesn't emit electromagnetic radiation at any wavelength of greater intensity than nowadays detector's threshold sensitivities;
(b) it doesn't block light from background objects, at any wavelength;
(c) it is more spread-out than stars, lying beyond galaxy disks, and even between galaxies.

Dark matter candidates

The very first consideration about which entity the missing matter could be has to do with its own nature, that is, of what elements it could be constituted. Just by analyzing its elusiveness, two possibilities immediately arise: (1) dark matter is comprised of ordinary matter, particularly dispersed, or (2) it consists of exotic matter that, although ubiquitously distributed, cannot get trapped into detectors.

The former of the two nature's category for candidates corresponds to matter just made of protons and neutrons – matter as it is "usually" constituted – and thus technically referred to as 'baryonic'; while by opposition, the latter group is just called 'non-baryonic'.

Baryonic dark matter

Regarding baryonic dark matter, the two "natural" candidates are: (1) massive objects whose existence has already been confirmed or at least are "highly probable", but lying so far away that remain invisible, or (2) large distributed volumes of gas with elusive properties.

The dim-massive-objects alternative is a good one. It includes *white dwarfs* (stars that have already exhausted all their thermonuclear fuel, so barely radiating thermal energy), *extrasolar planets*, *brown dwarfs* (starlike objects not massive enough to initiate thermonuclear processes), *neutron stars* (very compact stars composed almost entirely of neutrons), and *black holes* (objects whose gravity is so strong that no radiation can escape). As all of those massive candidates are expected to live in the halos – outer regions of galaxies – they are collectively called *Massive (Astrophysical) Compact Halo Objects* – or just 'MACHOs' for short ***[5]***.

Other than MACHOs, the remaining alternative for baryonic dark matter is hydrogen gas – not in vain, it represents already ¾ parts of the visible matter – but being somehow camouflaged in such a way that turns it invisible ***[6]***.

Loads of hydrogen gas would be presently undetectable whether heated to about one million degrees and uniformly spread between galaxies – 'hot diffuse gas' – or cooled down to only a few Kelvin degrees, and assembled into small dense clouds – 'cool gas clouds'.

Non-baryonic dark matter

Non-baryonic dark matter candidates correspond to exotic subatomic particles that do not interact electromagnetically – otherwise their radiation would be detected. Individually considered, they would interact with matter on extremely rare occasions, but collectively considered, their gravitational effect would become tangibly due to the huge amounts of such particles that supposedly exist.

Necessarily, those weakly interacting particles should be very stable, so non-baryonic candidates have to be relic particles from the early universe – where conditions were radically different. At the earlier moments after the Big Bang – the explosion of all space from which the universe emerged – the ubiquitous extreme density made all particles to be constantly colliding, and thus exchanging energy. The logical consequence of this process was an 'equipartition' of the available energy, that is, all particles acquiring on average the same kinetic energy ***[7]***.

Based on this assumption, non-baryonic candidates have been further subdivided by cosmologists between low mass particles moving very fast – referred to as 'hot dark matter' – or high mass slow moving particles – 'cold dark matter'.

While there is an obvious candidate for hot dark matter – the already known neutrino – the possibilities for cold dark matter are far more speculative, all suggested by theories that have not yet been confirmed experimentally. Any of such candidates is generically referred to as a 'WIMP' – for *Weakly Interacting Massive Particle*[2].

Among the more than 30 hypothetical particles currently proposed for WIMPs, those with better promising chances are the 'axion' and the 'neutralino'. Both particles have been predicted by different theories developed for a simple final solution for the unification of elementary particles and the forces that govern them. Neither of them would emit or absorb electromagnetic radiation, nor move fast, but neutralinos would have much more mass than axions ***[8]***.

The following table summarizes all possible dark matter candidates:

Dark matter nature	***Principal characteristic***	***Suggested candidates***
Baryonic	massive objects	MACHOs (brown dwarfs, white dwarfs, neutron stars, black holes)
	dispersed gas	Hot Diffuse Gas
		Cold Lumpy Gas
Non-baryonic	fast moving ('hot') particles	Neutrinos
	slow moving ('cold') particles	WIMPs (axions, neutralinos, etc)

[2] Neutrinos are also 'weakly interacting massive particles', particularly after they were confirmed as massive particles at the end of last decade. However, the term 'WIMP' is applied almost exclusively in reference to cold dark matter candidates, leaving neutrinos out of its coverage.

Which dark matter candidates are the best ones?

Having MACHOs been accreted from gas and dust clouds which almost certainly happened inside galaxies, chances are that no multitude of them could be wandering outside galaxies. This serious argument circumscribes the MACHO solution basically for just the missing matter in galaxy halos.

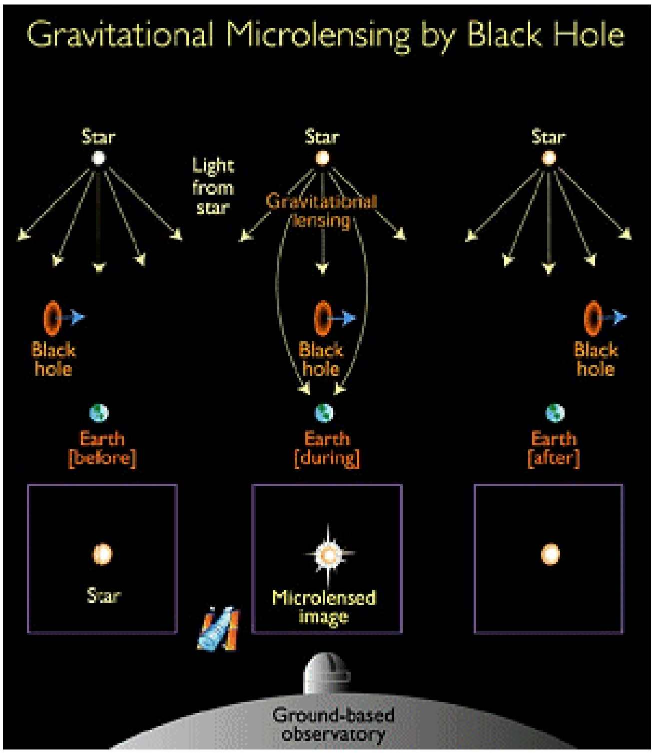

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Figure 4
The microlensing effect: when a previously undetected MACHO (like the shown black hole or any other type) happens to pass very close to the line of sight to a distant star, its gravity acts as a lens that bends the starlight, thus making it to temporarily appear brighten.

MACHOs in galaxy halos have been deeply researched in the past years by means of the 'microlensing' effect. As Figure 4 shows, if a dense invisible MACHO (like the suggested black hole) happens to pass between the Earth and a distant star, the gravitational curvature of space around the MACHO will deflect and focus that starlight, making the stellar brightness to provisionally increase. Although MACHOs nature would remain anyway unknown, its quantitative population can thus be estimated ***[9]***.

According to the mass of those effectively detected MACHOs, white dwarfs seem to be the best bet for them. Brown dwarfs appear far less abundant as expected, and the scarcity of characteristic by products released from the processes that produce neutron stars or black holes seems to also discard them as plentiful candidates ***[10]***.

Up to date, microlensing events by MACHOs are the strongest evidence of dark matter successfully detected. Extrapolating results obtained from the Milky Way's halo, there has to be considerable more mass in MACHO objects than in ordinary halo stars, although not representing more than about 20 % of the dark matter halo ***[11]***.

Although intracluster gas can exist in substantial amounts – theoretical works show it to be as much as the mass of stars in galaxy clusters – it still would not be large enough to hold galaxies together.

In short, baryonic dark matter certainly exists, but far less than the required to become the sole solution. Even for halos, where baryonic candidates appear more "natural" than non-baryonic rivals, they simply are not quite enough. The missing dark matter preponderance has to lie in non-baryonic forms.

The neutrino hypothesis as the solution for the missing matter, although engaging, poses a problem. Computer simulations of galaxy evolution in the context of prevailing neutrinos as the dark matter solution show galaxies forming lately in dense clusters with large voids between them. Modern trustful observations conclude that this is not the case, as galaxies seem to have formed very early ***[12,13]***.

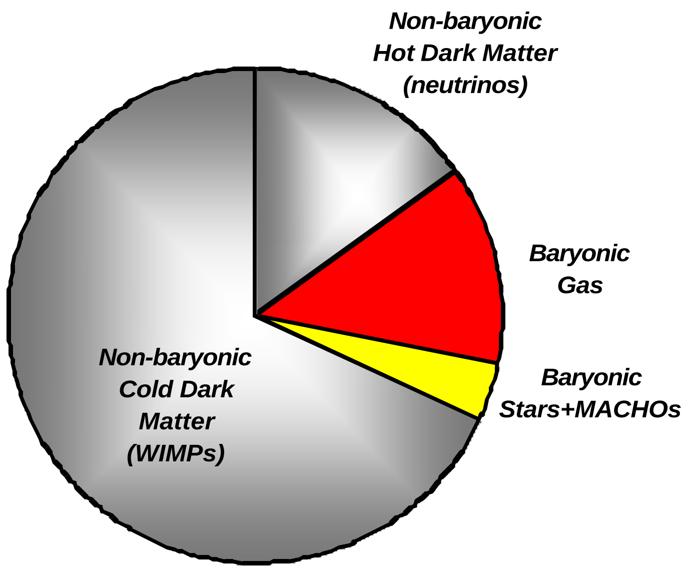

Figure 5
Estimated distribution of the nature of the overall mass of the universe
(percentage values have been roughly assigned, especially those corresponding to each type of non-baryonic dark matter, as their relative relationship is highly speculative)

Contrarily, simulations with exclusively or largely cold dark matter fairly reproduce the early galaxy formation and galaxy distribution like it is currently observed. This makes cold dark matter theory the most plausible presently solution – although not all roses[3]. In spite of

[3] A cloud on the horizon has recently appeared as WIMPs do not seem to be congregated in the centre of galaxies as they should to be, but these are preliminary results ***[14]***.

some dark matter actually contained in neutrino population, by far the prevalence would correspond to WIMPs ***[15]***. Figure 5 presents a diagram showing the present idea about how roughly the overall mass of the universe is distributed.

The following table summarizes the pros and cons of each one of the possible dark matter candidates:

Suggested candidates	***Pro-arguments***	***Con-arguments***
MACHO: brown dwarfs	Proved existence; very hard to detect	No yet evidence to be near as abundant as requested
	Bottom line: ***A minority amid MACHO candidates***	
MACHO: white dwarfs	Proved existence; very hard to detect; already observed MACHOs with right corresponding mass	No good alternative for young galaxies; implies the existence of much more helium than observed
	Bottom line: ***Although best MACHO candidate, a tiny fraction of DM***	
MACHO: neutron stars, black holes	High confidence in their existence; very hard to detect; can involve a lot of matter	Expected to be much scarcer than other MACHOs; no evidence of 'by-products' that should have been notorious
	Bottom line: ***A minority amid MACHO candidates***	
Hydrogen gas	It is already ¾ parts of the visible matter	Very difficult that the huge missing amounts would not have been yet detected
	Bottom line: ***Probably a tiny fraction of missing DM***	
Neutrinos	Proved existence; its mass has also been proved	Computer simulations not properly coincide
	Bottom line: ***Certainly account for some part of DM, although minority***	
WIMPs	Theoretically produced in the Big Bang in right amounts and properties; correct simulations	Existence not yet proved at all
	Bottom line: ***So far, the best candidate for DM's majority***	

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Ongoing experiments in search of non-baryonic dark matter

Presently, there are two basic ways for researching non-baryonic dark matter. One method consists in artificially recreate the reigning conditions of the early universe, while the other attempts to effectively detect samples of such exotic particles.

The first alternative implies searching for new massive particles originated in collisions at the highest-energy particle accelerators. In this regard, high hopes are deposited in the European organization CERN [4], where a new and by far world's largest powerful accelerator will be in full operation from next year ***[16]***.

The second alternative face the fact of dealing with almost non-reactive particles, thus looking for intrinsic very feeble "signals" always in the context of comparative high-level "noise" environments. Therefore, one of the biggest challenges to resolve is to provide proper shielding in order to avoid false signals from any kind of radiation – being either terrestrial or cosmic – which makes to place the detectors deeply underground.

To discover an exotic particle the detector must be capable of registering small nuclear recoil energies – those resulting from the very rare occasions when a neutrino or WIMP strikes a detector nucleus head-on and cause an elastic recoil – that only happens about once per day for every 10 kg of detector mass ***[17]***.

The energy of the recoiling nucleus can thus be detected by means of:

(a) a slight rise in temperature may be recorded ('phonon-based' detection)
(b) an electric charge may be liberated ('ionization-based' detection)
(c) a photon may be emitted ('scintillation-based' detection)

The most sensitive experiments looking for dark matter, currently being performed at leading institutes [5], are scintillation-based using sodium-iodide (NaI) detectors. However, all types of detectors are needed, as they result mutually complementary – each one having different characteristics. Therefore, any trustful WIMP detection will have to be based on different methods, otherwise its credibility would remain controversial ***[18]***.

Results from those exciting experiments will promissory cast new light on the dark matter issue in the immediate future. Nevertheless, its final and definite solution, hopefully expected for the first quarter of this century, will still require new observations and detectors, as well as more sophisticated models that go beyond the purely gravitational dynamics of cold dark matter to also include the currently unconnected world of particle physics ***[19]***.

Conclusions

The existence of dark matter is by now well established; it is its actual nature that remains uncertain. Although some dark matter has been corroborated to exist in baryonic forms – particularly as MACHOs inside halos – the remaining overwhelming majority still lies hidden in non-baryonic disguises.

Modern theories attribute the bulk of dark matter basically to be comprised of WIMPs, while neutrinos certainly occupying a secondary proportion. Although all WIMP candidates

[4] 'CERN' stands for *Centre Europeen Reserche Nucleaire*, addressed in Geneva, Switzerland.
[5] Such as the *UK Dark Matter Collaboration* program (UKDMC) in North Yorkshire, England, and the *Italian-Chinese Dark Matter* experiment (DAMA) in Gran Sasso, Italy [18].

still are highly speculative, models based on cold dark matter solutions are currently the most appealing ones.

Many sophisticated programs are being carried on in order to detect elusive WIMP particles, while research closely mimicking early universe conditions is also being under development. WIMP exact nature can be discovered just around the corner, and chances are that the crucial dark matter issue becomes fully resolved within the next two decades. Likely, the whole iceberg will soon show completely visible.

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