2 The realm of the nebulae

"In the Kingdom of Heaven all is in all, all is one, and all is ours."
Meister Eckhart

In order to 'weigh' the ordinary matter of the universe, it is clearly not enough just to estimate the contribution of the baryons through the study of a single astronomical object, however near it may be. This is our inevitable conclusion, but fortunately, the Milky Way has many siblings in the sky, making it possible to adopt a more global approach to the population as a whole.

Island universes

This term, together with 'nebulae', was formerly used to designate what we now refer to as galaxies. That these are systems exterior to our own Milky Way was finally recognized at the time of The Great Debate[1] between astronomers Harlow Shapley and Heber D. Curtis. Leaving aside those cataloged as irregulars (which were in the majority in the early universe), these systems have characteristic shapes, allowing them to be classified into two great families: spiral galaxies (both ordinary and barred) are disk-shaped, with a central bulge of stars, and elliptical galaxies look like soccer balls or rugby balls (Figure 2.1). How these cosmic denizens were formed, their properties, and especially the existence of the three main families, continue to be the subjects of intensive research. It is, however, established that the driving force playing an essential role in their gestation is that of gravity, causing dark matter and baryons to congregate until a galaxy is born; and it is gravity that still maintains their stability and creates the morphologies already mentioned.

As this process of formation proceeded, the disk-shaped galaxies came to acquire rotational motion: a boon for astronomers, since, using Newton's Laws of gravitation, they can deduce the total mass of a spiral system from its

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[1] The Great Debate revolved around the question of whether the observed 'nebulae' were extragalactic or not. See http://antwrp.gsfc.nasa.gov/diamond_jubilee/debate.html

A. Mazure and V.L. Brun, *Matter, Dark Matter, and Anti-Matter: In Search of the Hidden Universe*,
Springer Praxis Books, DOI 10.1007/978-1-4419-8822-5_2,

Figure 2.1 Some examples of different types of spiral and elliptical galaxies. (Upper left) The Sc type spiral galaxy NGC 5457 (M101) in Ursa Major. (Lower left) The SBb type barred spiral galaxy NGC 1300 in Eridanus. It is thought that our Milky Way is a SBc type barred spiral galaxy. (Upper right) The more or less spherical E0 type elliptical galaxy NGC 4458 in Virgo. (Lower right) The more ellipsoidal E5 type elliptical galaxy NGC 4660 in Virgo (NASA/STScI and the Hubble Heritage Team (STScI/AURA)).

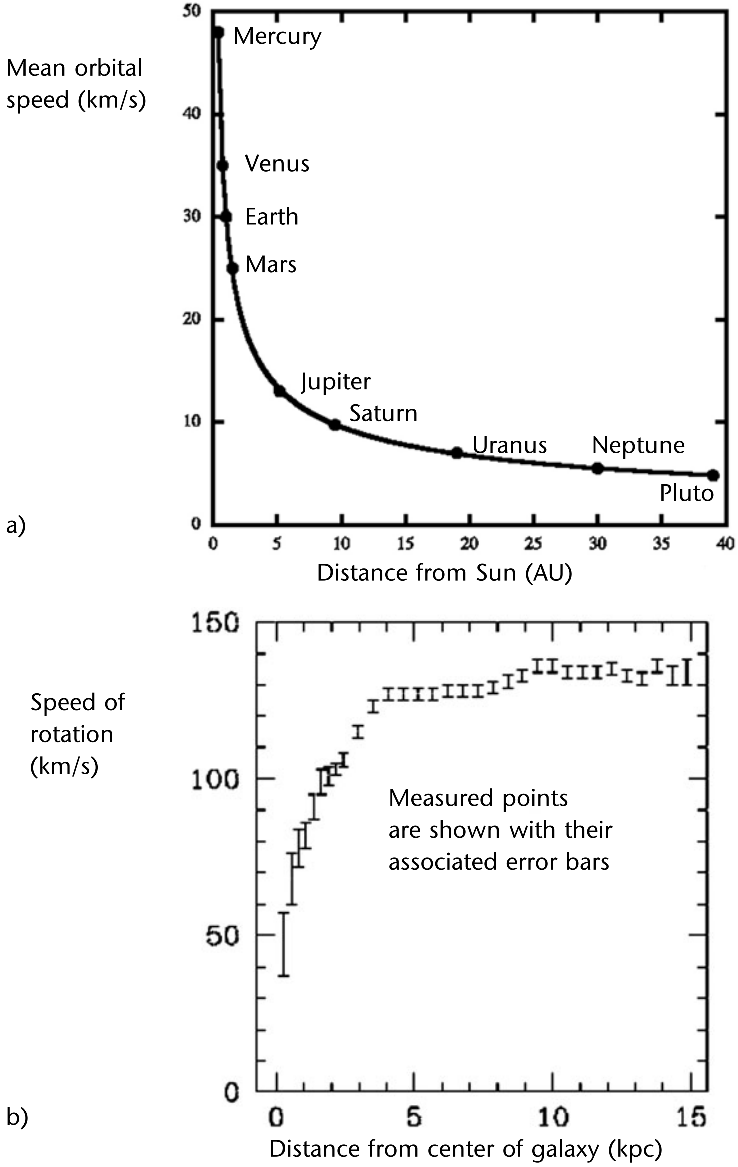

Figure 2.2a) Orbital velocities of the planets around the Sun as a function of their solar distances. The curve matches that predicted by Newton's theory of gravitation, if all the mass is situated within the planetary orbits. **b)** Rotation curve of a spiral galaxy, i.e. variation in rotational velocity with distance from the centre of the galaxy. Velocities are determined from the shifts in wavelength (Doppler Effect) in the radiation emitted by different zones of the galaxy. The obvious difference between this curve and that of the planetary orbits shows that the mass is not concentrated in the central parts, where most of the stars are to be found.

observed rotation. By careful measurement of the rotation curves[2] (Figure 2.2b) of these objects and the application of gravitational laws, their masses can readily be determined. The mass arrived at by this method is known as the ‘dynamical mass’, to distinguish it from estimates determined by other methods. This is an essential value, since it is a reliable indicator of the total mass of galaxies, obtained without having to deal with the contents of these objects in detail. So we can ‘weigh’ spiral galaxies, and also the other types, without having to count all their component stars.

As we shall see later, comparison of the results obtained by the different techniques will bring about consequences both unexpected and fundamental...

Iceberg galaxies

We encounter a problem when observing external galaxies: they are ever more distant and ever fainter, and therefore increasingly difficult to observe. What is more, because of these great distances, we can no longer see or count their individual stars. There is, however, one advantage – their apparently small size in the sky means that they can easily be imaged in a single exposure, and we can immediately estimate their total luminosity. Moreover, if these objects lie near enough to us in the universe, we can easily study their properties in various regions of the cosmos. This is the strategy (the establishment of a database of 100 million external galaxies) successfully adopted by researchers pursuing the Sloan Digital Sky Survey (SDSS). The SDSS program is one of the most ambitious and influential surveys ever realized in the history of observational astrophysics.[3] The SDSS uses a dedicated 2.5-meter telescope at Apache Point Observatory, New Mexico (Figure 2.3), equipped with two powerful special-purpose instruments. The 120-megapixel camera images 1.5 square degrees of sky at a time, about eight

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[2] Spiral galaxies rotate, and the velocity of any region of a galaxy can be measured by studying the apparent change in frequency (known as the Doppler Effect) of the light emitted. Measurement of the change in frequency (or wavelength) gives an indication of the rotational velocity. This velocity can be compared to the distance from the center of the galaxy to establish a rotation curve. Generally, velocity reaches a plateau at a considerable distance from the center (Figure 2.2b). Spiral galaxies do not spin as if they were solid bodies (like, for example, a spinning top), with velocities proportional to distance from the center), and neither do they mimic the motion of the planets around the Sun, where velocity decreases with distance (Figure 2.2a).

[3] For further information, see http://www.sdss.org.

Figure 2.3 Image of the 2.5-meter Sloan Digital Sky Survey telescope at Apache Point Observatory in New Mexico (from the website of the SDSS http://www.sdss.org/gallery/).

times the area of the full Moon. A pair of spectrographs fed by optical fibers measure spectra of (and hence distances to) more than 600 galaxies and quasars in a single observation. A custom-designed set of software pipelines keep pace with the enormous data flow from the telescope.

Over eight years of observations by the telescope dedicated to the program (SDSS-I, 2000-2005; SDSS-II, 2005-2008), with 40 researchers ensuring coordinated data management and analysis, SDSS obtained deep, multi-color images covering more than a quarter of the sky and created three-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars. Meanwhile, SDSS is continuing with the Third Sloan Digital Sky Survey (SDSS-III), a program of four new surveys using SDSS facilities. SDSS-III began observations in July 2008 and will continue operating and releasing data through 2014.

The SDSS team's precise spectroscopic studies have enabled them to determine simultaneously the positions, luminosities and stellar-population details of many thousands of galaxies, and thereby the typical MLRs, thought to be universal. This hypothesis is certainly a valid one, given the area covered by the SDSS, which ensures a truly representative sample. With a great deal of telescope time and a great volume of perspiration behind them, the researchers have used the phenomenal mass of data acquired to estimate the amount of baryons concentrated within the stars ($\Omega_{b\text{-}stars}$, adapting the notation Ω_b already encountered in the previous chapter).

It will be seen immediately from Table 2.1 and Figure 2.4, when comparing this estimate of the baryon content of galaxies with the total contents as expressed by Ω_{tot}=100 percent, that the contribution of the stars to the whole is a feeble one: about 0.25 percent of the whole, and a tiny fraction of the ordinary matter of the universe. But this is by no means the end of the story. Above, we mentioned how the total mass of galaxies can be measured by, for example, analyzing the rotation curves in the case of spirals. This allows us to determine what we have called the dynamical mass, which can also be measured for a sufficiently representative sample of these objects. The broad

Table 2.1 Fractions of ordinary (or baryonic) matter existing as stars and gas within galaxies, compared with total energy/matter in the cosmos, expressed as different parameters of Ω_b.

Nature of ordinary matter	Contribution to total energy/matter content of universe	
Stars	$\Omega_{\text{b-stars}}$	~0.25 percent
Gas in atomic form (hydrogen, helium)	$\Omega_{\text{b-HI + HeI}}$	~0.06 percent
Gas in molecular form	$\Omega_{\text{b-HII}}$	~0.016 percent
Total		**~0.32 percent**

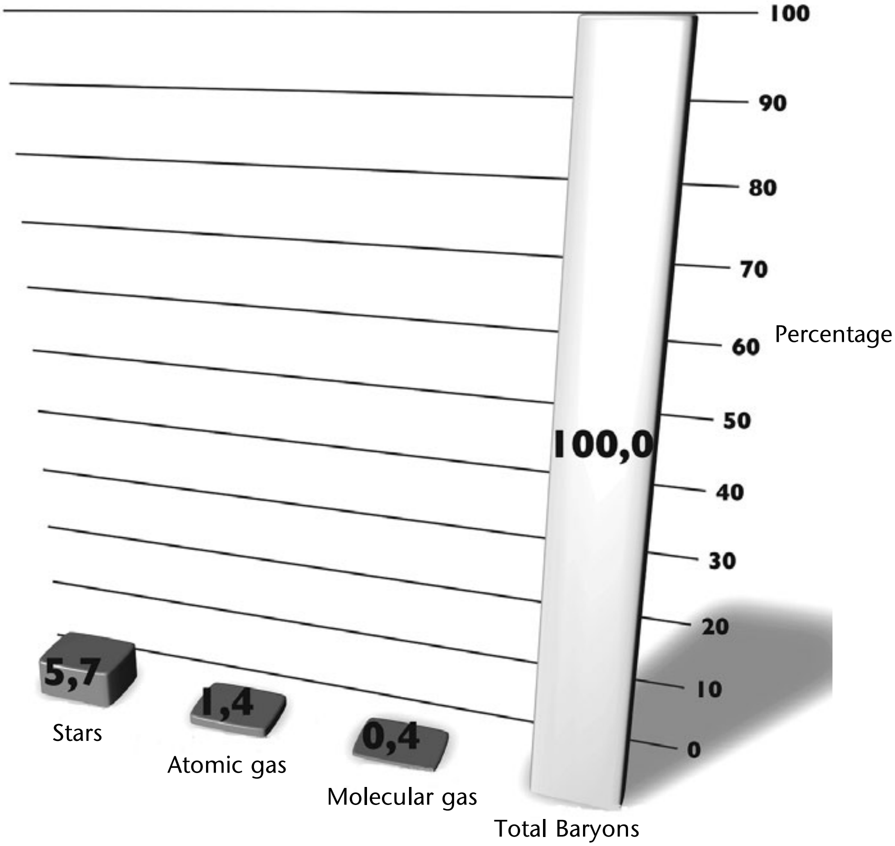

Figure 2.4 Comparison of quantities of ordinary matter as detected in the stars, atomic gas and molecular gas within galaxies, and the total contents of this baryonic matter in the cosmos. It is readily seen that a very large fraction is unaccounted for.

comparison of this estimate of the total mass of galaxies with that of the baryons detected shows a deficit in the latter of a factor 5-10. What can be the reason for such a discrepancy? Either there are many baryons hidden within galaxies which have evaded detection in spite of the scrupulous surveys of the astrophysicists, or some other explanation will have to be found... So we will have to widen our investigations if we wish to sign off our cosmic accounts.

Galactic fauna

So where are the missing baryons hiding? As in the case of the Milky Way, we must also bring into the reckoning the ordinary matter present in the form of gas and dust, or in any other form that does not emit visible light: gas, both atomic and molecular, and also dust (a term used to describe small grains of matter in the interstellar medium, usually present as silicates, the scientific word for sand). The gas, essentially the atomic hydrogen present in the interstellar medium, is very dilute, and cold. It emits no visible light (unlike, for example, the gas in a neon tube, which is dense and excited by the difference in electric potential to which it is subjected). The only way in which this interstellar gas can be detected is through absorption (the gas absorbs light from a background star at characteristic wavelengths, and the composition and density of the gas can then be determined), or through emission, *via* the so-called 'fine-structure' transition of atomic hydrogen. This transition gives rise to radiation at a wavelength of 21 centimeters (radio waves), so radio telescopes must be used to detect this gaseous component. A similar problem is found in the case of molecular gas, whose transitions are less energetic than those of its atomic counterpart. Here too, radio telescopes are indispensable. Various surveys have revealed a whole range of cosmic 'fauna' within the interstellar medium: from simple molecules like carbon monoxide, water and methane, to very complex organic types containing, for example, twenty carbon atoms, sometime arranged in rings, such as benzene.

All these detailed studies have enabled astrophysicists finally to identify the various contributions of these elements. It seems a little paradoxical to summarize the results of all this considerable expenditure of time and energy in just a few numbers in a table: such is the scientist's lot... But the most frustrating thing about the data so painstakingly acquired is that the contributions of the different elements are, in the final analysis, so small: just a few per cent (Table 2.1 and Figure 2.4), and the value we arrive at for the density parameter of the baryons present in galaxies, in the classic forms of stars or gas, is only about 0.32 percent!

In conclusion, in spite of a seemingly complete inventory, the discrepancies mentioned have not been accounted for. On the one hand, baryons in galaxies do not constitute the majority of the energy/matter content of the cosmos, and on the other, they do not even seem to constitute the mass responsible for the observed rotation curves of spiral galaxies (not to mention other kinds). This gulf between the measured total and (in the broad sense) luminous masses of the galaxies (and the same is true of clusters of galaxies) leads us to infer the existence of hidden mass or dark matter,[4] in order to be able to explain the discrepancy. Seen in this way, luminous matter is only the visible 'tip of the iceberg' of matter as yet undetected directly. The frustrating

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[4] Hidden mass or dark matter is probably matter composed of particles as yet hypothetical, but envisaged by certain extensions of the model of particle physics. The idea of dark matter is the response to the problem of hidden mass, a problem brought about by the analysis of the dynamics of galaxies and clusters of galaxies and the existence of gravitational 'mirages'.

conclusion has in fact engendered new questions. What is the nature of this dark matter? Might there be, for example, baryonic matter that has so far eluded us?

Stars and MACHOs

Observations of spiral galaxies, and indeed of clusters of galaxies, show indisputably that their dynamics, i.e. the rotation of the spirals and the motions of the galaxies within their groups or clusters, cannot be explained in terms of their visible contents alone. So, we can either call into question the laws of gravitation, or infer an abundant amount (about 80 percent of the total mass) of hidden matter. The first hypothesis has not been favored by physicists, although it has not been abandoned. If the second is to be pursued, then what kind of matter can it be that keeps itself hidden from astronomers?

The stars so far mentioned are, by definition, luminous bodies. Their light originates in thermonuclear reactions deep within them. We know for example that our Sun, which has been shining for some five billion years, will continue to shine for a further five billion years, since the fusion of hydrogen in its core can last that long. However, for these nuclear reactions to be triggered, conditions of density and temperature at the center of the star must be fulfilled. It has been shown[5] that a star's mass is the most important factor that determines its lifetime. Paradoxically, the more massive a star the shorter its lifetime.

For a star to be stable, the weight of its successive layers must be counterbalanced by high pressure from within, preventing it from collapsing inwards. If this pressure is high enough, the nuclei of atoms which under normal conditions in a gas will repel each other because of electrostatic repulsive forces, may be fused together, emitting energy which is then radiated away by stars. Knowing the relationship between pressure and temperature, we can deduce that a star needs to be of a mass at least equal to one-hundredth of the mass of the Sun for this cosmic reactor to be switched on. If this mass is not attained, the nuclear fires will not be ignited, and the body in question will not have energy to radiate. Such dark bodies are sometimes known as 'failed stars', but a better label for them is brown dwarfs (Figure 2.5) or MACHOs.[6] It is certainly tempting to consider MACHOs as

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[5] See, for example, *Exploding Superstars* by A. Mazure and S. Basa (Springer/Praxis, 2009).

[6] MACHO is the abbreviation for MAssive Compact Halo Object, as opposed to the WIMP (Weakly Interacting Massive Particle), also a candidate for dark matter.

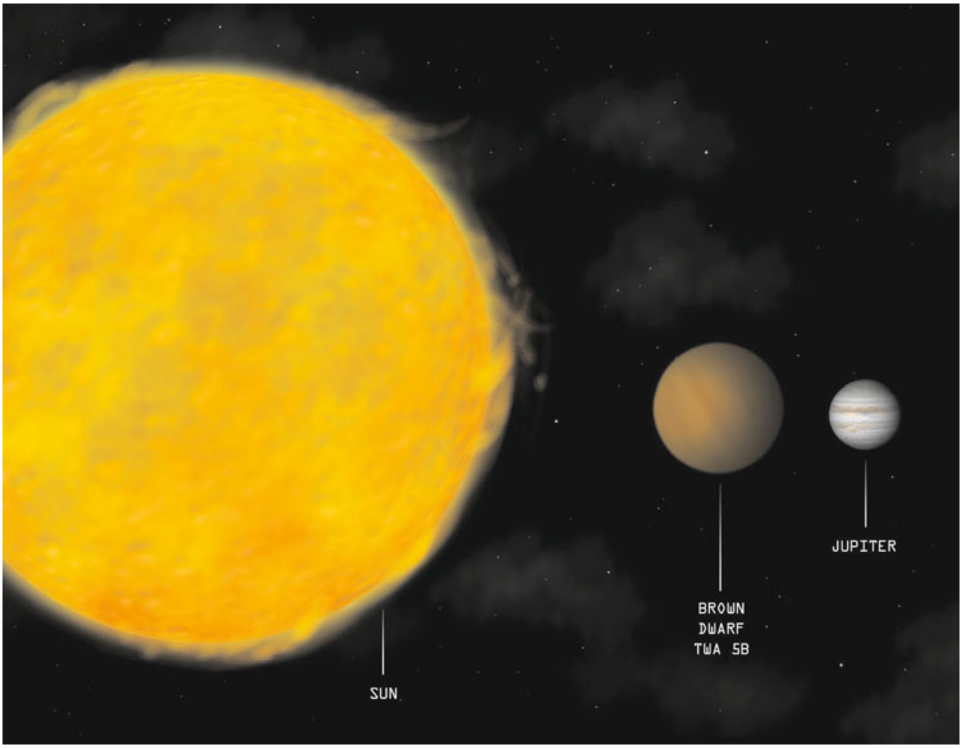

Figure 2.5 The approximate size of a brown dwarf (center) compared with the Sun (left) and the giant planet Jupiter (right). Although brown dwarfs are similar in size to Jupiter, they are much more dense and emit infrared radiation, whereas Jupiter shines with reflected light from the Sun (NASA/CXC/M. Weiss).

potential candidates for the coveted title of 'missing mass', or 'dark matter'. They are, by definition, dark stars (at least as far as visible radiations are concerned, since their temperatures, typically a few hundred degrees, mean that they emit only in the infrared). They are probably very common objects, since it seems that, in general, there are greater numbers of stars among the less massive types. So what they lack in size, they could make up for in number, and their total mass might be enough to constitute the hidden mass in the form of dark baryons.[7]

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[7] Since the hunt for baryons has proved in part fruitless, the hypothesis of dark baryons has arisen: these emit no radiation and are therefore practically undetectable. They may exist in the form of brown dwarfs or as very cold molecular hydrogen.

The saga of the dark baryons

In the 1980s, a Polish researcher called Bohdan Paczynski achieved fame by demonstrating that the brown dwarfs scattered throughout the galactic halo might be involved in gravitational (micro-)lensing effects. We know that, according to Einstein and his theory of General Relativity, the motions of celestial bodies can be explained not by gravitational forces between them but rather by the local curvature of space caused by the presence of mass at a given location. Now, this applies not just to the paths of the planets, but also to electromagnetic radiation and to the particles that constitute it: photons. So, a beam of light will be deflected in the vicinity of a massive object, as if it were being viewed through an optical lens. The two phenomena are closely analogous, whence the term 'gravitational lensing'. These lensing effects can be highly spectacular when photons emitted by a more distant galaxy encounter a cluster of galaxies composed of several hundred members, with a total mass of as much as a hundred thousand billion (10^{14}) times that of the Sun. The distorted image of the galaxy is seen as if through the bottom of a glass bottle. The relative positions of the remote object(s), the lensing cluster of galaxies, and the observer may combine to create magnificent gravitational arcs or lensed arcs (Figure 2.6). These distorted and amplified images of the

Figure 2.6 This Hubble Space Telescope image of a rich cluster of galaxies called Abell 2218 is a spectacular example of gravitational lensing. This cluster of galaxies is so massive and compact that light rays passing through it are deflected by its enormous gravitational field. This phenomenon magnifies, brightens, and distorts images of more distant objects (Andrew Fruchter (STScI) et al., WFPC2, HST, NASA).

distant galactic light sources (sometimes called mirages) are caused by the presence of the intervening cluster of galaxies along the paths of the photons emitted. In accordance with the laws of gravity, the rays of light will be curved by massive objects. Not only are the images of the distant objects distorted, but they are also amplified, appearing brighter due to the concentration of the light rays (Figure 2.7). Therefore, the intervening clusters of galaxies are sometimes known as 'gravitational telescopes'.

The phenomenon of lensing may occur in the case of objects other than distant galaxies and intervening clusters. For example, a brown dwarf in the halo of our Milky Way galaxy may act as a micro-lens upon the light from a star within the Large Magellanic Cloud, one of the Milky Way's satellite galaxies. This would seem a worthwhile way of detecting potential MACHOs. However, since these objects are in constant motion within our Galaxy, the phenomenon of amplification will be but a transient event to an observer on Earth. Fortunately, there are millions of stars within the Large Magellanic Cloud which might be momentarily 'brightened' by Galactic brown dwarfs. Encouraged by the potentialities of this technique, several large-scale surveys (e.g. EROS, AGAPE, MACHOs, OGLE, DUO...) were begun during the 1990s, especially in the direction of the Large Magellanic Cloud. One difficulty however is that, in spite of the enormous numbers of objects in play (several million), the probability of observing the effect remains fairly low. The expected rate is only a handful of detections per million stars, and the duration of the phenomenon depends on the mass of the lensing body and the relative motions of both 'lens' and source. The phenomenon can last from some tens of days in the case of a lens of the order of a tenth of a solar mass, to one day for a lens of less than a millionth of a solar mass.

Surveying the Large Magellanic Cloud, the Andromeda Galaxy or the central regions of our own Galaxy, as several groups have done, requires large imaging systems (Schmidt cameras or CCD arrays). Also, powerful computers are needed to compare the thousands of images, hunting for some fleeting variation in the brightness of a star. The analysis is further complicated by the existence in the cosmos of all kinds of objects whose brightness varies. This difficulty is countered by the simultaneous use of a range of filters when observing, since the phenomenon of gravitational lensing is independent of wavelength, unlike a great number of other transitory stellar phenomena.

It would seem therefore, after several years of work studying tens of millions of stars, that the mass represented by brown dwarfs contributes but little to the total mass of ordinary baryons. Dark baryons are therefore not the 'white knights' coming to the rescue of hidden matter, and the question already posed remains: are there other kinds of missing baryons?

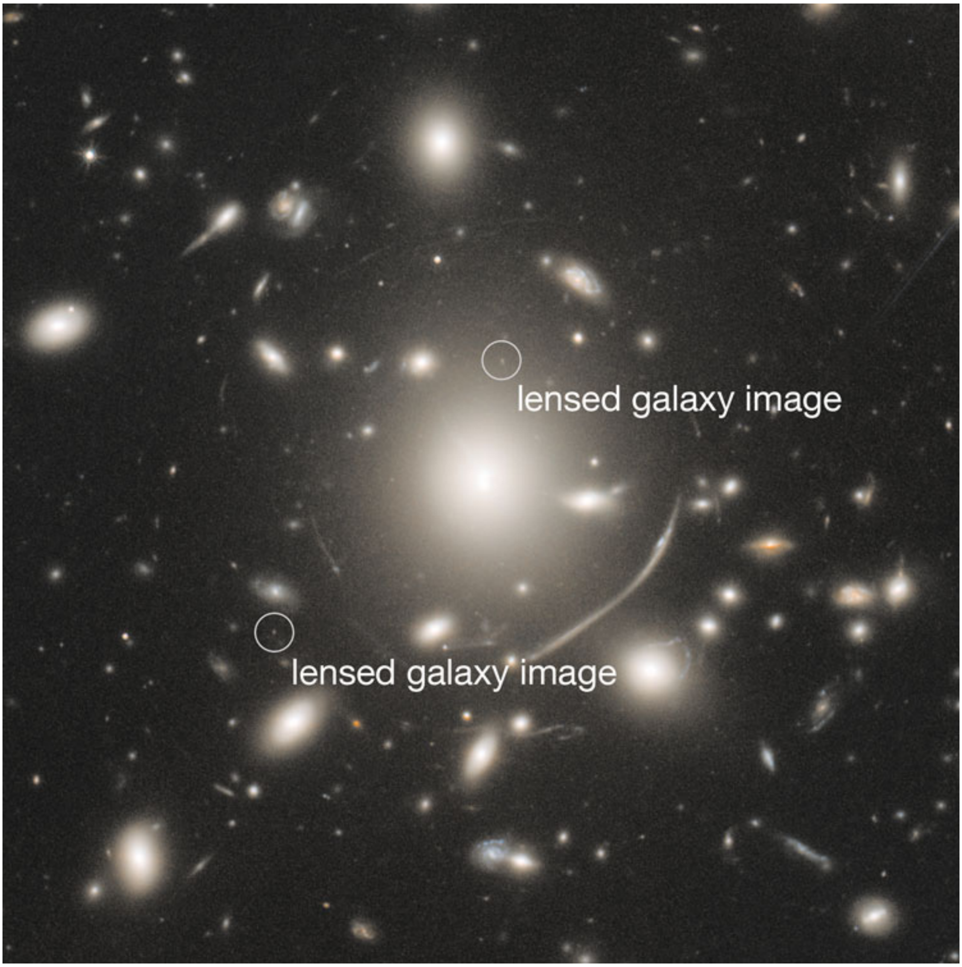

Figure 2.7 Astronomers have used the technique of gravitational lensing to discover one of the youngest galaxies in the distant universe. The Hubble Space Telescope was first to spot the newfound galaxy. Detailed observations from the W.M. Keck Observatory on Mauna Kea in Hawaii revealed the observed light dates to when the universe was only 950 million years old. The distant galaxy's image is being magnified by the gravity of a massive cluster of galaxies (Abell 383) parked in front of it, making it appear 11 times brighter, one of the consequences of gravitational lensing (NASA, ESA, J. Richard (Center for Astronomical Research/ Observatory of Lyon, France), and J.-P. Kneib (Astrophysical Laboratory of Marseille, France), with thanks to M. Postman (STScI)).

More about galaxy clusters

Clusters of galaxies are the largest and most massive stable gravitationally-bound structures to have arisen so far in the process of cosmic structure formation in the universe (Figure 2.8). They typically contain from a few hundred to 1,000 galaxies (if there are fewer than 50, they are known as groups of galaxies), together with extremely hot X-ray emitting gas and large amounts of dark matter. Their total masses may be of the order of 10^{14} to 10^{15} times that of the Sun, contained within a volume typically 5 million to 30 million light years across. Their considerable mass makes them privileged targets for studying the nature and distribution of matter in the cosmos. Within such a cluster, the spread of velocities for the individual galaxies is about 800–1000 kilometers per second.

Clusters of galaxies were first identified in the course of galaxy counts using Schmidt cameras. Astronomers George Abell and Fritz Zwicky came to realize that, in some localized areas of the sky, there were significantly greater

Figure 2.8 Hubble Space Telescope image of the magnificent Coma Cluster of galaxies, one of the densest known galaxy collections in the universe. Hubble's Advanced Camera for Surveys viewed a large portion of the cluster, spanning several million light years across. (NASA, ESA, and the Hubble Heritage Team (STScI/AURA).)

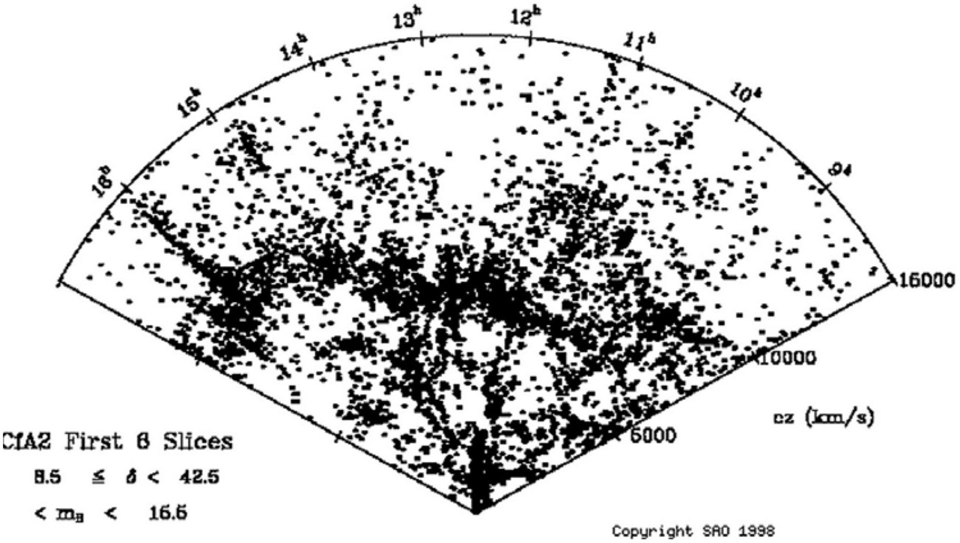

Figure 2.9 In the 1980s, the Harvard Smithsonian Center for Astrophysics initiated one of the first large surveys of the universe with the aim of mapping the distribution of galaxies by measuring their velocities v, and thereby their distances d, using Hubble's Law ($v = Hd$). This revealed the existence of vast voids, filaments and 'walls'. We also see large elongated structures, all in the direction of the observer: these correspond to clusters of galaxies containing several hundred objects, and we are measuring the radial component of their velocities within the cluster.

numbers of galaxies than were recorded elsewhere. Thus, they showed the existence of clusters and groups of galaxies, nowadays listed in two great catalogs which bear their names.

The galaxies within the cluster are in equilibrium due to gravitational effects essentially created by dark matter. They all pursue their trajectories through the cluster at velocities reaching several hundred kilometers per second. Astronomers can measure these motions with the aid of spectrographs, using the Doppler Effect caused by the apparent shift in the wavelength of the radiation emitted by each galaxy.

This proper motion complicates the representation of clusters: the distances of the galaxies are in fact derived from their radial velocities (in the direction of the observer) using the formula for the expansion of the universe. However, if a fraction of this velocity represents velocity within the cluster, then the measured distance is falsified. This is why clusters appear elongated on charts such as that shown in Figure 2.9. To measure the internal velocity dispersion of a cluster, it is necessary to establish the distance common to all the galaxies (the size of the cluster being small compared with

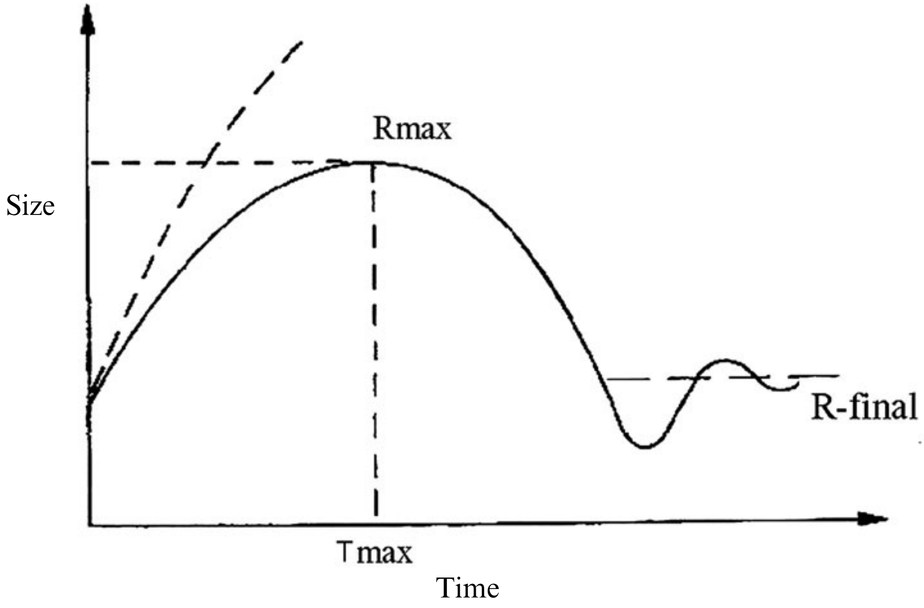

Figure 2.10 When a structure forms, it must first of all decouple from the expansion. Here we see the radius around a fixed mass M, which will become a distinct structure. Time elapses towards the right. At first, the mass continues to expand (solid line), at a rate which slows in relation to the mean rate of the expansion of the universe (dashed line). The relative density becomes greater and greater relative to the rest of the universe. The time will come (T_{max}) when the density reaches the critical density that allows the structure to collapse upon itself. Then the expansion will be reversed until the structure reaches virial equilibrium, and kinetic energy is balanced by potential energy. During the collapse, the velocities of agitation are higher, until the equivalent 'pressure' balances out the forces of gravity. We then obtain a secular stable structure, of radius R_{final}.

its distance from us), then deduce the internal velocity from the measured velocity and the overall velocity of the cluster.

The impressive development of multi-object spectroscopy during the 1990s meant that the velocities of several hundred or even of thousands of objects could be measured simultaneously, and the universe could thus be surveyed directly and not just through stellar images. These new-style surveys allowed clusters of galaxies to be identified and cataloged.

Clusters of galaxies, like galaxies themselves, originated in the growth of 'clumps' initially present in the cosmic fluid. Under the effects of gravitation, a small excess in density increases with time (equivalent to redshift), such that at a given moment it becomes large enough for the region of space concerned to 'separate' from the general expansion, at redshift z_{sep} (Figure 2.10). The forming system will continue, of course, to follow the expansion

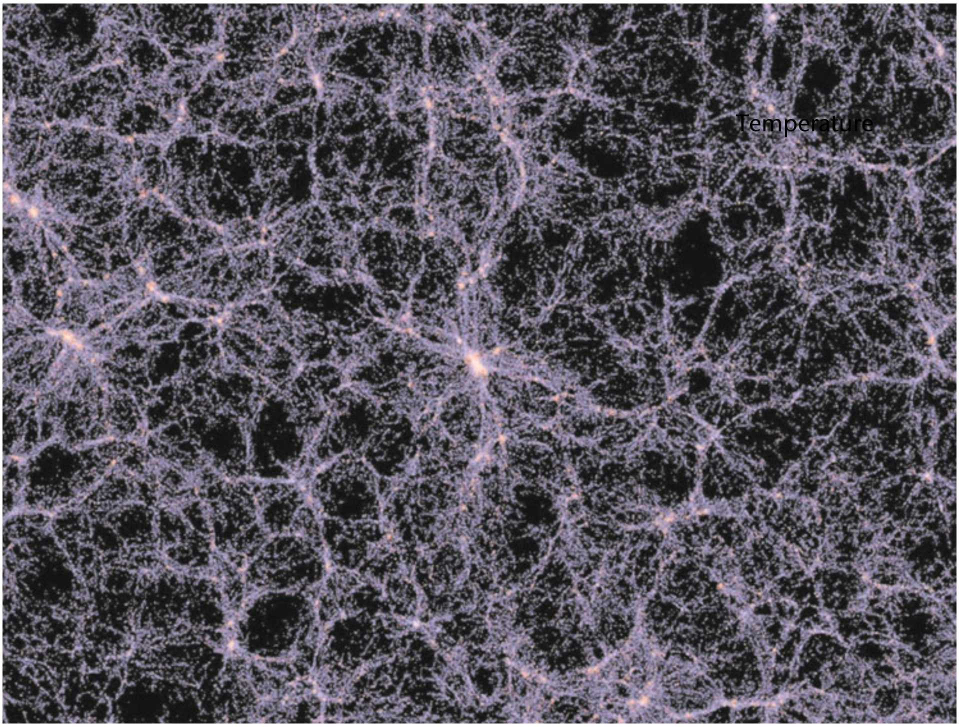

Figure 2.11 Large-scale structure of the universe. A slice of a computer simulation of our universe by the Virgo Consortium. The nodes, filaments and walls of light make up the large scale structure that we can observe in outer space.

generally, but will for some time experience internal oscillations before reaching a definite stability at size R_V. The system has become stable, or what is known as virialized, with virial radius R_V of the order of a few million light years.

Clusters and their contents (dark matter, galaxies and hot gas) are globally in equilibrium, held together by the common gravitational potential essentially created by dark matter. In the large-scale distribution of structures, clusters of galaxies appear as 'knots' at the intersection of filaments~~,~~ and which themselves surround large empty voids (Figure 2.11). In fact, the peripheral zones of clusters are continuously fed with galaxies and gas 'flowing' along these filaments, gradually populating the cluster to the accompaniment of violent effects (tidal effects, interactions with the gas between clusters...) within the environment that they encounter. Only at the cores of clusters is there any real stability.

We now know that, in spite of their name, clusters of galaxies are composed mostly of dark matter ($\sim$ 80 percent), X-ray emitting gas ($\sim$ 15 percent) at temperatures of 10 million to 100 million degrees, and finally

Figure 2.12 Composite image of a collision between two clusters of galaxies. Superposition of X-ray emissions from hot gas and the projected mass in the galaxy cluster 1E 0657-56, familiarly known as the 'Bullet Cluster'. (X-ray: NASA/CXC/CfA/M.Markevitch *et al.*; Lensing Map: NASA/STScI, ESO WFI, Magellan/U.Arizona/D.Clowe *et al.*; Optical: NASA/STScI, Magellan/U.Arizona/D.Clowe *et al.*) The mass distribution projected on the sky corresponds to the mass of the clusters as reconstructed by gravitational lenses (deformations of background galaxies). Two clusters can easily be distinguished. The smaller cluster, at right, seems to have traversed, in the manner of a cannon ball, the larger one at left. During this collision, the hot gas of the subcluster has encountered the hot gas of the large cluster, and has been braked such that the two gaseous areas are closer together than the two masses. To the right we clearly see a shock wave in the shape of an arc, resulting from the passage of the smaller cluster. The projected X-ray gas and masses are also superimposed on the optical image showing the individual galaxies. The different behaviour during the collision of the hot gas and the stellar masses, including dark matter, allows us to separate the three components and test the models (after Clowe *et al.*, 2006).

galaxies ($\sim$ 5 percent). With the development of multi-wavelength observational techniques, it has become possible to analyze and identify in detail the contents of these systems, and even to 'visualize' their diverse components. For example, the object which has become known as the 'Bullet Cluster' turns out to be the result of a collision between two clusters. This system has been observed in detail at both visible and X-ray wavelengths (Figure 2.12).

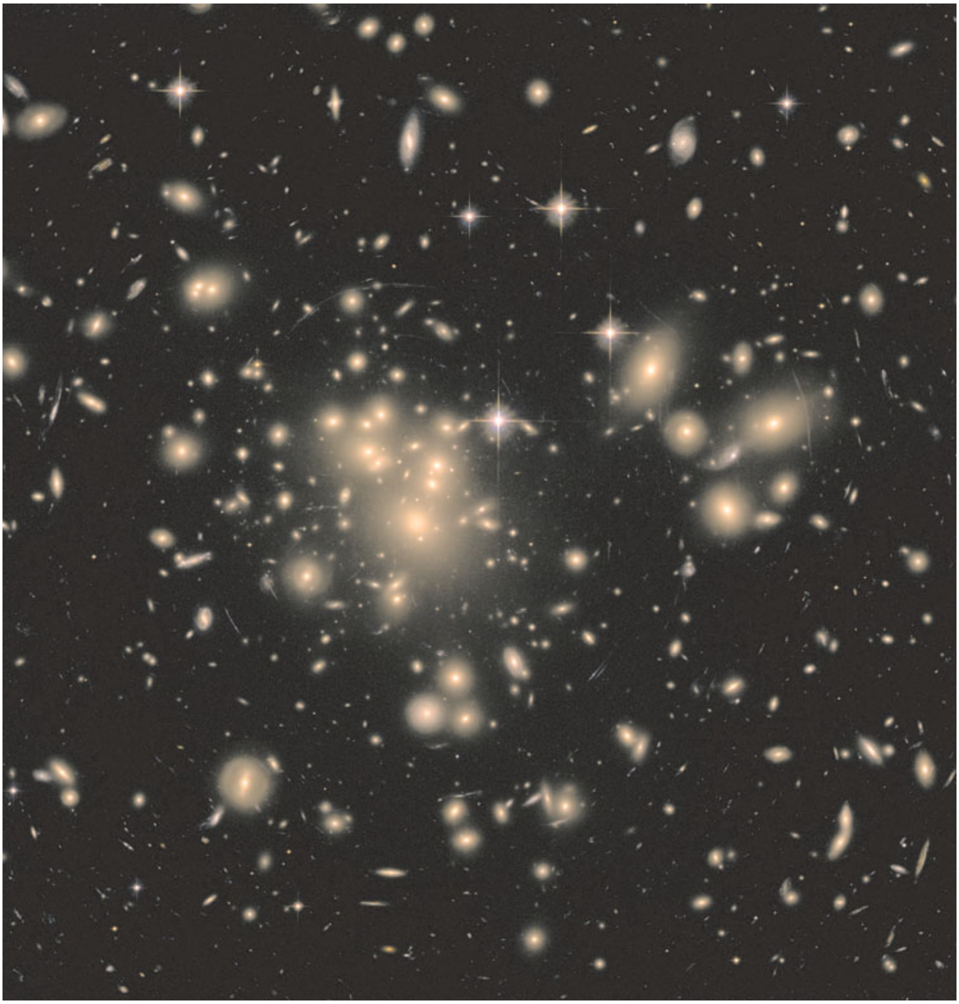

Figure 2.13 These two NASA Hubble Space Telescope images reveal the distribution of dark matter in the center of the giant galaxy cluster Abell 1689, containing about 1,000 galaxies and trillions of stars. The galaxy cluster resides 2.2 billion light years from Earth. Hubble cannot see the dark matter directly. Astronomers inferred its location by analyzing the effect of gravitational lensing, where light from galaxies behind Abell 1689 is distorted by intervening matter within the cluster. Researchers used the observed positions of 135 lensed images of 42 background galaxies to calculate the location and amount of dark matter in the

cluster. They superimposed a map of these inferred dark matter concentrations, tinted blue (above), on an image of the cluster taken by Hubble's Advanced Camera for Surveys (facing page). If the cluster's gravity came only from the visible galaxies, the lensing distortions would be much weaker. The map reveals that the densest concentration of dark matter is in the cluster's core (NASA, ESA, D. Coe (NASA Jet Propulsion Laboratory/California Institute of Technology, and Space Telescope Science Institute), N. Benitez (Institute of Astrophysics of Andalusia, Spain), T. Broadhurst (University of the Basque Country, Spain), and H. Ford (Johns Hopkins University)).

Here we see (in red) the distribution of the hot gas, revealed through its X-ray emissions as detected by NASA's Chandra X-ray Observatory. This X-ray gas represents, essentially, the baryons within the cluster. The galaxies and the stars they contain, as seen on the image, in fact constitute only a small part of the total baryonic mass, and this itself is only a small fraction of the total. Most of this mass is dark matter (blue), which is of course undetectable directly since it emits no radiation. It manifests itself through gravitational lensing effects upon background galaxies, effects which allow us to reconstitute and visualize its distribution within the cluster. The first striking thing about this image is the superposition of the distribution of galaxies upon that of the dark matter, both spatially shifted with respect to the distribution of the X-ray emitting gas. This results from the fact that these diverse components do not react in the same way to the collision between the two clusters. This is a great boon for astrophysicists, meaning that they can 'see' separately, and 'weigh', the different contributions to the mass. Also, the analysis of this cluster is a very strong argument in favor of the existence of dark matter, since theories of modified gravity (MOND) cannot easily account for the phenomenon.

Astronomers using the Hubble Space Telescope have also derived the distribution of dark matter in the center of the giant galaxy cluster Abell 1689. This cluster contains about 1,000 galaxies and trillions of stars and lies 2.2 billion light years from Earth. Again, astronomers inferred the location of the dark matter by analyzing the gravitational lensing effects, as light from galaxies behind Abell 1689 is distorted by intervening matter within the cluster. Researchers used the observed positions of 135 lensed images of 42 background galaxies to calculate the location and amount of dark matter in the cluster. If the cluster's gravity came only from the visible galaxies, the lensing distortions would be much weaker. The map reveals that the densest concentration of dark matter is in the cluster's core (Figure 2.13).

As well as galaxies and dark matter, clusters contain hot gas, which is essentially left over from the initial gas involved in its formation. Like the galaxies, the gas is in equilibrium within the common gravitational potential, which means that it acquires sufficient energy to reach temperatures of the order of many millions of degrees, becoming ionized and emitting X-rays corresponding to this range of temperatures. With instruments of the sensitivity of those carried by XMM-Newton or Chandra, it is possible to carry out large-scale surveys of the sky in which groups and clusters of galaxies appear as zones of extended emissions, easily distinguishing them from stars, galaxies or quasars which can also be sources of this range of wavelengths.

Photons of 'fossil' cosmological radiation at 3 degrees Kelvin (the cosmic background radiation or CMB) bathe the cosmos, including its clusters of galaxies. They therefore interact with the hot intragalactic plasma, and in particular with the electrons of this plasma. These photon-electron interactions tions cause the energy and therefore the frequency of the photons of the

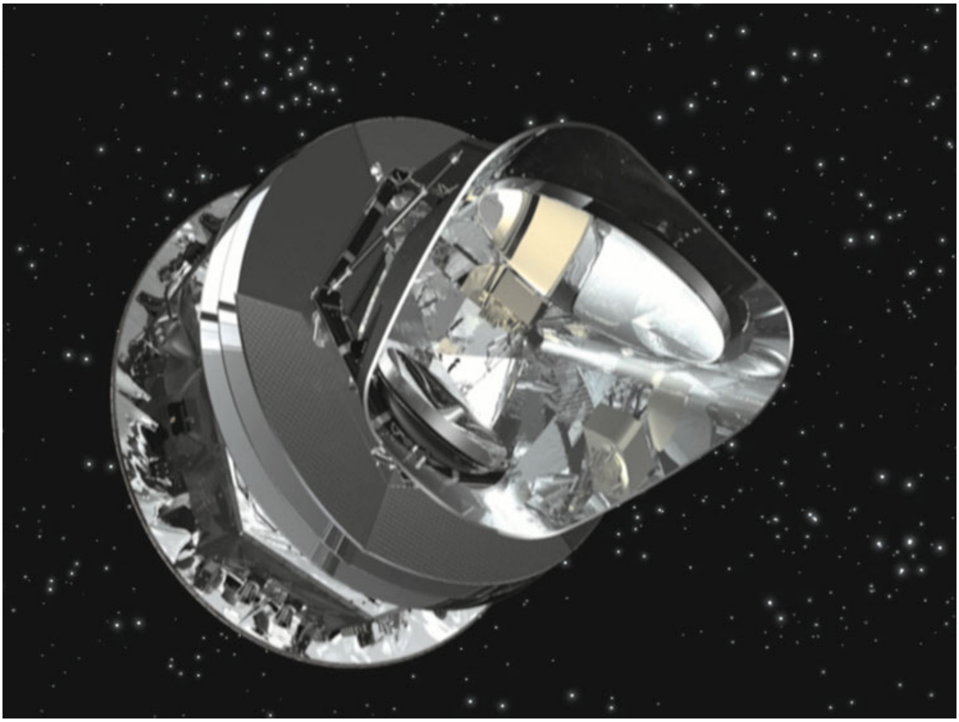

Figure 2.14 Artist's impression of the Planck satellite, launched on 14 May 2009 (together with the Herschel space telescope), on a mission to map the anisotropies of the cosmic microwave background radiation field over the whole sky, with unprecedented sensitivity and angular resolution. Planck was formerly called COBRAS/SAMBA. After the mission was selected and approved (in late 1996), it was renamed in honor of the German scientist Max Planck (1858-1947), Nobel Prizewinner for Physics in 1918. Fifty days after launch, Planck entered its final orbit around the second Lagrangian point of the Sun-Earth system (L2), at a distance of 1.5 million kilometers from Earth.

CMB to be modified. This so-called 'Sunyaev-Zel'dovich effect' can be measured at millimetric wavelengths, and the Planck satellite (Figure 2.14), launched in 2009, has detected, during its first year of observations, about 200 clusters of galaxies in this way.

Finally, whatever method of detection is used, we can count clusters in space, and at various spectral redshifts. These counts, as a function of volume or redshift, constitute a powerful test of cosmological models and the determination of associated parameters.

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