The MACHOS' AGAPE

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Résumé

Measurements of the density of the Universe lead to the conclusion that the major part of its matter content does not shine. Among all possible hypothesis as to the nature of that dark matter, AGAPE focuses on MACHOS, also called *missed stars* because their mass is too low for the thermonuclear reactions responsible for a star's luminosity to take place. In order to detect these nearly invisible objects, AGAPE looks for microlensing events that betray the presence of MACHOS. After three years of data intake, the unique method, called *pixel lensing*, developed by AGAPE for the analysis of the data, was proved reliable thanks to the convincing microlensing events that were found, and other international teams working in the same field of interest have begun using that technique with our help.

1. The density of the Universe

1.1. *Observational Cosmology*

In the name of the laboratory figures the word *Cosmology*, a science that aims at the description and understanding of the Universe as a global entity, its spatial properties and evolution. I am concerned with a part of cosmology called *Observational Cosmology* or *CosmOb*, that regroups theory and observation, faithful to the idea that cosmology's large scale questions, that reach the limits of our observational possibilities†, can only be solved by a constant exchange between both. CosmOb can be seen as an information freeway between observation and theory. One of these fundamental questions concerns the "dark side" of our Universe, directly linked to its evolution...

1.2. *Theoretical motivation*

The dynamical evolution of our Universe is described by the Friedmann equation :

$$H^2 = \frac{8\pi G\rho_m}{3} - \frac{k}{a^2} + \frac{\Lambda}{3} \tag{1}$$

where H is the Hubble constant‡, so named after the great astronomer Edwin Hubble, who discovered it in 1929, a the scale factor, ρ_m the mean matter density, k the universal curvature (which only possible values are -1, 0 and 1) and Λ the cosmological constant which is still devoid of easy physical interpretation. The curvature parameter k is critical, because it says whether the Universe is open ($k = -1$ or $k = 0$, expansion carries on forever) or closed ($k = 1$, expansion will eventually stop, replaced by a contraction back to the Big Crunch, the inverse of the Big Bang). By dividing each side of equation (1) by H^2, we find :

$$\Omega_m + \Omega_\Lambda + \Omega_k = 1 \tag{2}$$

with :

$$\Omega_m = \frac{8\pi G\rho_m}{3H^2} \qquad \Omega_\Lambda = \frac{\Lambda}{3H^2} \qquad \Omega_k = \frac{-k}{a^2H^2} \tag{3}$$

Therefore, the parameter Ω_m, linked to a measurable quantity ρ_m as shown in (3) tells us, under certain conditions, whether the Universe is open or closed : if Ω_m is lower that one, and supposing that the Universe has a null cosmological constant Λ (so that $\Omega_\Lambda = 0$), we have $\Omega_k > 0$, leading to $k = -1$, i.e. the Universe is open, expanding forever. Knowing the fate of the universal expansion means measuring the Ω_m parameter, which reduces to the measurement of ρ_m.

1.3. *The need for dark matter*

Knowing the approximate mass over luminosity ratio M/L of stars (given by stellar evolutionary models), we can, by integrating on all wavelengths the light emission of the galaxy, thus obtaining L_{galaxy}, measure the amount of visible, shining, galactic mass if we make good use of the following relation :

$$\frac{M_{galaxy}}{L_{galaxy}} = cte \cdot \frac{M_{sun}}{L_{sun}} \tag{4}$$

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† In terms of scale, the Earth is to the Universe what the atom is to the Earth.

‡ $H \simeq 75$km/s/Mpc, which leads to a Universe aged $\frac{1}{H} \simeq 14.5$ billion years.

where L is the luminosity, and where the constant *cte* depends on the appropriate galactic model§.

If in parallel we study galactic rotation curves, it is then possible to demonstrate the existence of a large fraction of dark matter. Rotation curves plot the rotation speed of galactic objects (stars, or gas clouds) with respect to their distance from the galactic center (around which they are in orbit). Newtonian laws, that suffice at this scale†, give :

$$v^2 = \frac{GM}{R} \tag{5}$$

with G as the universal gravitational constant, R the distance to the galactic center and M the mass contained in a sphere of radius R centered on the galactic center. The measurements yield two surprising results. First, the dynamic galactic mass is ten times as big as the luminous galactic mass mentioned above, proving that as much as nine tenths of the galactic mass is made up of non-luminous matter, that is $\Omega_m^{galactic} \simeq 0.1$ et $\Omega_m^{visible} \simeq 0.01$ (see relation 2). Secondly, the rotation curve is flat, well beyond the greatest distance at which luminous matter is observed, proving that the speed is constant on large scales, which is only possible if M increases like R in equation (5).

To sum up, galactic matter is mostly dark, and not concentrated in the luminous region, because its mass increases as R when we move away from it, which leads us to believe that *the distribution of galactic matter does not follow that of luminous matter.* We may also suppose the existence of a roughly spherical distribution of dark matter around the galaxy, disjoint from the luminous part, making up what is called a *dark halo.*

2. The nature of dark matter

2.1. Many candidates

But what then is the nature of this galactic dark matter ? The candidates divide up in two categories : the baryonic, so called because they are made up of Earth-like atomic matter, and the non-baryonic, made up of exotic stuff.

In the first category, we find, among others, interstellar gas clouds, ultra dense objects such as black holes and neutron stars, together with MACHOS, which will be described shortly.

In the second category, we shall only mention WIMPS (Weakly Interacting Massive Particles). Examples of WIMPS are the neutralino, the lightest particle of the supersymetric model (SUSY), and the neutrino, a well known particle which mass is not yet well defined. If the neutrino has a mass of a few eV, then it could make a significant contribution to dark matter in the Universe. Recent results from the SuperKamiokande experiment (see [1]) show that the neutrino has a mass of a few 10^{-2}eV, which is way too small to account for the proportion of observed dark matter.

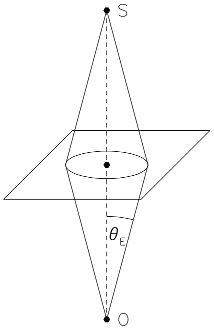

Figure 1. *Gravitational microlensing effect*

2.2. The MACHOS

We have already mentioned MACHOS (Massive Compact Halo Objects) as baryonic candidates for dark matter. MACHOS are a group of objects that could account for the existence of the dark halo that is shown to exist when studying galactic rotation curves, as explained in the previous section. A MACHO may take the form of a *brown dwarf*, a ball of Hydrogen and Helium gas, the same as for stars, but which mass lies between $10^{-7} m_{sun}$, the limit of gas evaporation, and $10^{-1} m_{sun}$, representing the limit beyond which thermonuclear reactions take place, making a star out of the gas ball : this explains the name *missed star* coined in to describe a brown dwarf. Apart from its solid kernel, the planet Jupiter is in all aspects a good example of what a brown dwarf looks like.

But these objects do not shine, so the question is how to hunt them down ? If they are close enough to a star, they might reflect the star's luminosity, making possible their detection under favourable conditions‡. But here, we are dealing with a brown dwarf that belongs to the MACHO category, and thus is not in orbit around a star, but rather in the suburbs of the galaxy, making it impossible to detect it directly with a telescope : this is the right time to be intoduced to the microlensing phenomena.

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§ The key idea is the *luminosity function*, that provides us with the distribution of the type of stars in the galaxy.

† General Relativity does not yield significantly different results.

‡ Unfortunately, on pictures taken, the star's luminosity often hides the one reflected by the orbiting brown dwarf.

3. The gravitational microlensing effect

When a massive object comes close to the line of sight between an observer and a star[§], general relativity predicts a bending of the light rays leading to an increase of the star's apparent luminosity : it is the *gravitational microlensing* effect. Figure 1 represents the *source* (star) in S, the observer (the Earth) in O, and, between them, the *lens* (the MACHO); the light rays take the shape of two lines bent by the curvature effect, and separated by an angle θ_e or *Einstein's angle*. We see that the observer receives two light rays, making him believe that there are two light sources, lying in the direction of the two lines. The angle θ_e between the two virtual images produced by the deflection of light is extremely small. As an example, if we consider a lens in the halo of our own galaxy, $D_{ol} = 8\,\text{kpc}$[||], and a source in the Large Magellanic Cloud, $D_{os} = 50\,\text{kpc}$, we find :

$$\theta_e \simeq 10^{-3}\sqrt{\frac{M_{lens}}{M_{sun}}}\ \text{arcsec} \ll 10^{-1}\ \text{arcsec} \tag{6}$$

where 10^{-1} arcsec is the lower limit for angular resolution using today's technology. Therefore, both images overlap on our pictures, their combination leading to an amplification of the star's apparent luminosity that commonly ranges from 1.5 to 10.

By monitoring through time the light flux received from a star (we then obtain what is called a *light curve*, see figure 2) belonging to a far away galaxy, we can look for some increase in the apparent luminosity, signature of a microlensing effect. It is therefore possible to detect halo brown dwarfs that come near to the line of sight : when approaching, the brown dwarf induces an increase in the star's apparent luminosity which then reaches a maximum before decreasing. This increase/decrease is seen as a bump on the light curve, and this is what we are looking for. That bump is the footprint left by the brown dwarf when it travelled in the neighbourhood of the line of sight that goes from the Earth to the observed star.

The geometric setup of the observer+lens+source required for the detection of a brown dwarf through a microlensing effect only occurs seldomly, with a probability as low as 10^{-6} for a given star at any time. To compensate for that low probability, the usual method is to keep watch over millions of stars (usually 10^7 stars), and wait for one of them to experience a luminosity increase : the famous bump, visible on the example in figure 2.

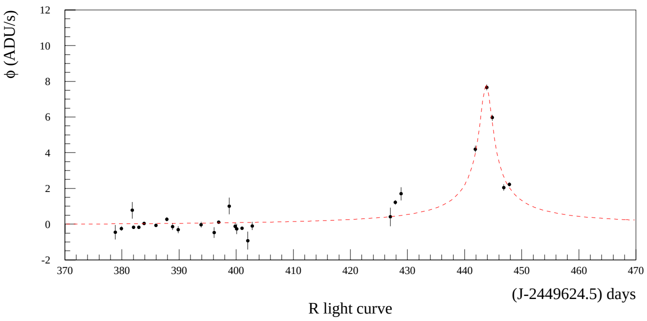

Figure 2. *Light curve for event Z1 : each point represents the intensity of the same pixel taken at a given date.*

4. Unicity of AGAPE

The AGAPE collaboration takes advantege of an idea quite different from the one that consists to monitor the intensity of 1 million well defined stars, called *resolved stars*. In order to explain that idea, it is useful to introduce the concept of a *pixel*.

When taking pictures of the night sky, we use an electronic camera, called CCD. What we have to keep in mind is that the camera divides the sky in 1 million small squares, called pixels, and each of them collects the luminosity that it receives from the sky. Now, to cover the sky with small squares is the same as covering it with a grid. It is obvious that each grid-square then contains a certain number of stars. Lets us now imagine that a star in one of those pixels experiences a microlensing effect, its apparent luminosity then increases, implying that the total luminosity collected by the containing pixel also increases.

This is the idea from which originates the pixel method used by AGAPE : *instead of monitoring the luminosity of 1 million stars, we monitor the luminosity collected by each of the 1 million pixels that make up our electronic picture.* One of the advantages is that each pixel, in fact, captures the light of around 200 stars[†] enabling us to monitor 200 million stars instead of 1 million with the usual method ! Let us remember this : we do not care about monitoring the light flux of this or that star, we content ourselves with taking pictures of the night sky, and, on these pictures, we keep track of the intensity of all pixels, because we know that each pixel implicitly monitors 200 stars on average.

The data analysis is divided into four parts :

- Monitor the evolution of each pixel's intensity on all our images.

[§] The *line of sight* is a fictive line joining the observer to the star.

[||] 1 kpc = 10^3 pc = $10^3 \cdot 3,6$ light years, keeping in mind that our galaxy, the Milky Way, is 10^5 light years in diameter.

[†] We study the M31 Galaxy in Andromeda at a distance of 750 kpc, and taking into account the 0.3 arcsec of sky covered by each pixel, this gives approximately 200 stars per pixel.

- The successive images give, for each pixel, a *light curve* as shown on figure 2.

- We look for increases in the light flux due to a microlensing event (big programs look automatically for bumps on light curves here at our lab), an example of which is given on figure 2.

- Additional quantitative criterias help us in refining our selection. One such criteria is the fit of the theoretical microlensing effect, known as the *Paczynski curve*, on our selected light curves, in dashes on figure 2.

5. AGAPE today and tomorrow

Today, AGAPE looks for low mass MACHOS, which means short microlensing events (narrow bumps on the light curve).Figure 2 shows such an event, code named Z1, the subject of a recent paper (see [2]). For these researches, we make use of the data taken at the telescope Bernard Lyot, at the Pic du Midi in the french pyreneans : 160 nights of observation from 1994 to 1996, with 50% good weather.

In parallel, we keep on improving the quality of the computer algorithms used for the automatic events detection (the bumps on the light curves). We have to remember that CosmOb (observational cosmology) depends heavily on the weather for good observational quality. In a physics experiment concerning, let us say, a pendulum, it is easy to start everything over again and again, but this is unfortunately totally impossible in CosmOb : once the brown dwarf is gone, you cannot put it back to its starting position ! There lies the fundamental difference between an experimental and an observational science. Therefore, atmospheric turbulence is quite annoying because it might induce diffusion illusions for example, and these must be corrected for. This is what we mean when we talk about improvements : we introduce new or improved algorithms. Even if our technique has already proved its efficiency, we nevertheless find it useful to keep working on it.

Finally, let us mention that we have started applying our craftsmanship to data coming from collaborations with other international teams working in the field : the data from the Isaac Newton Telescope, in the Canary Islands, thanks to our collaboration with the english (B. Carr), or also from the MDM telescope at Kitt Peak, Arizona, thanks to our american collaborators (A. Gould). We have also begun a long-term partnership with the Capodimonte Observatory in Naples, Italy, with Mr Capaccioli, where we play the role of a service provider : they take the data, and we provide the analysis.

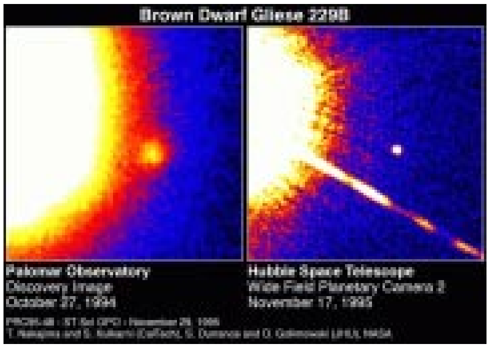

Figure 3. *Direct visual detection of a brown dwarf in the vicinity of a star.*

We also take advantage of the data collected by the Hubble Space Telescope (or HST) : once we have detected an interesting event, we wish to find out the star that has been microlensed. But by definition of our pixel method, we only have access to the pixel that has collected the flux information, and we do not know which one of the approximately 200 stars monitored by the pixel is the source of the event. Therefore, we look for a possible star candidate, at the estimated event position in the sky, on pictures taken by the HST in the appropriate sky region. This is interesting because the HST has a much better angular resolution† (one of the reasons being that the telescope roves over the atmosphere, and does not suffer from atmospheric turbulence) than Earth-bound telescopes, and is thus capable of making out stars that appear to us as background noise.

We shall conclude by reminding that the HST has already seen a brown dwarf : when it belongs to a solar system, the brown dwarf may be detected by its capacity, like Jupiter, to reflect the light received from the star around which it lies in orbit ‡. Figure 3 shows the power of the HST : two pictures of the Gliese 229b brown dwarf, first detected in 1994 with mount Palomar telescope, then in 1995 with the HST.

References

[1] Fukuda, Y. et al.: Phys.Rev.Lett. 81 (1998) 1562-1567 (hep-ex/9807003)
[2] Ansari, R. et al.: astro-ph/9812334, soon to be published in A&A.
[3] Wambsganss, J.: astro-ph/9812021.

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† 0.001 arcsec, as compared to 0.3 arcsec for earth-bound telescopes.

‡ This brown dwarf is no longer a MACHO, because it belongs to a solar system and not to the dark halo.