Cosmic rays in the classroom

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Cosmic rays in the classroom

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Abstract

We use the context of astroparticle physics to introduce several fundamental concepts in physics and astrophysics. An activity has been developed using inexpensive materials that allows the reconstruction of the impact point and arrival direction of a cosmic ray particle measured by the Pierre Auger Observatory. The activity includes the discussion of fundamental concepts such as conservation of energy and momentum, centre of mass, trajectory, coordinate systems, speed, geo-orientation, time references and sky observation.

Introduction

The explanation of fundamental concepts in innovative ways has been always a challenge for teachers. We present here the construction of an experiment that allows us to discuss several subjects at high-school level. The experiment is placed within a modern and contemporary physics context, including discussion of particle physics and astrophysics. On the other hand, the calculations involved remain in the framework of classical mechanics. This is one of the main features of this work, which gives the teacher the opportunity to explore modern and contemporary physics concepts in a classical formulation. At the same time, the experiment proposed here offers an alternative route, through an interesting and advanced scientific experiment, to discuss classical physics principles.

Astroparticle physics is a modern interdisciplinary subject in which particle physics and astrophysics come together. Since Hess discovered the cosmic origin of this radiation [1], many experiments and theories have contributed to the effort to advance our knowledge of the production mechanisms of particles with very high energy. From an educational perspective, astroparticle physics is a rich field to be explored. The connection between macroscopic (astronomical objects) and microscopic (fundamental particles) phenomena present in this research field offers a unique opportunity to develop important scientific concepts in the learning process of young students. Some important papers have explored this feature of cosmic-ray physics in the classroom [2–6]. However, most of them have focused on the use of sophisticated instruments and software by students. The activity proposed here has the advantage of being very cheap and simple.

The Pierre Auger Observatory [7] is an astroparticle physics experiment taking data and producing important results [8–10]. The observatory is situated in Malargue, Argentina and its main purpose is to study the highest energy particles ($E > 10^{19}$ eV). The Pierre Auger Observatory uses two detection techniques: an array of surface detectors and fluorescence telescopes. The surface detector is composed of 1660 individual stations covering 3000 km^2 overlooked by 27 fluorescence telescopes at four

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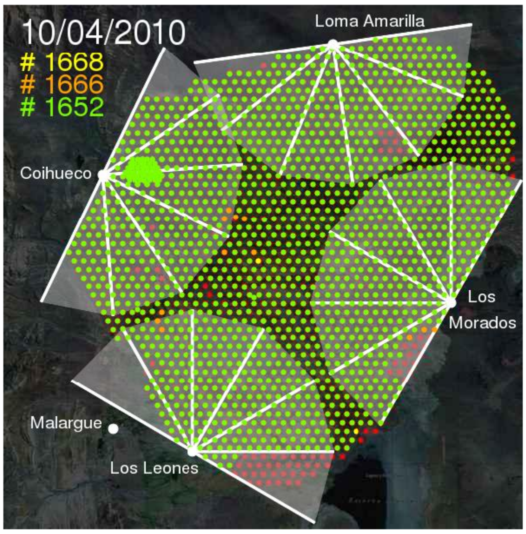

Figure 1. Pierre Auger Observatory. The white lines represent the field of view of the fluorescence telescopes. The map shows the status of the observatory on 10 April 2010. The dots of different colours represent the surface detectors. Each colour represents an operational status of the detectors.

sites. Figure 1 shows a schematic view of the observatory. Only the data from the surface detectors are used in this work. A picture of one individual surface detector is shown in figure 2.

The Pierre Auger Observatory has a successful outreach [11] programme which includes a visitor centre, participation of the local community in the experiment, talks around the world and the release of 1% of the measured events for public use[1]. These public events have been used in this work.

Basic information from an event measured by the Pierre Auger Observatory is given to the students and they are guided in the construction of a model that allows reconstruction of the direction of the first particle that entered the Earth's atmosphere. By knowing the exact time at which the event was measured, the student is able to point out on a sky map where the cosmic particle came from.

The arrival direction of cosmic particles is one of the most important pieces of information to be extracted from an astroparticle physics observatory. Other important pieces of information

[1] http://auger.colostate.edu/ED/.

Figure 2. One of the surface detectors of the Pierre Auger Observatory. The detector is filled with 12 tonnes of pure water. In the figure one can see the battery box at the left bottom of the detector, a solar panel and an antenna. It is also possible to see a dome on top which covers the electronics of the detector. The detector is fully autonomous and has no wire connection to the central data acquisition system.

are the energy and the type of the particles. If the arrival direction is known it is possible to correlate the particle with types of astrophysical sources. Such a correlation was first discovered recently by the Pierre Auger Observatory with active galactic nuclei (AGN) [8].

In summary, the analysis procedure of an event measured by the Pierre Auger Observatory goes from the signal as a function of time measured by an array of detectors on the ground to an astronomical object in the sky. The intention of this proposal is to guide the student along this path, from the micro- to the macrocosmos, discussing fundamental physics at each point.

In the next section we discuss the physics concepts, present the model construction and discuss its applicability.

Physics concepts

High-energy particles from the cosmos enter Earth's atmosphere and interact with the nuclei of the atoms in the air. The interaction produces a jet of secondary particles. Successive interactions result in a chain production of particles, as illustrated in figure 3. The development of these particles in the atmosphere is called an air shower. The first particle that started the shower is called the primary particle. The particles in

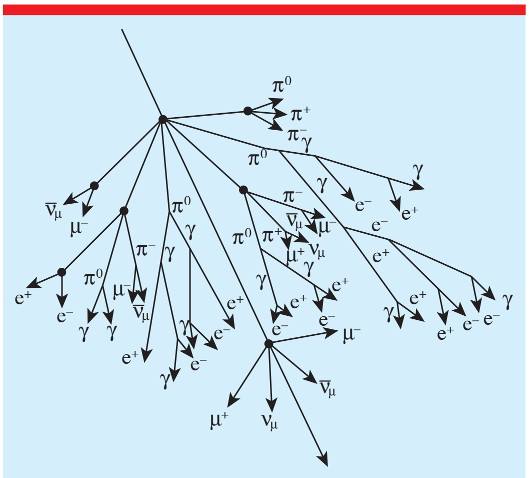

Figure 3. Schematic view of an atmospheric air shower. The particles shown are examples that are not in real proportion to the particles produced in a shower. The lateral size of a shower at the level of the Pierre Auger Observatory depends strongly on its arrival direction, energy and particle type. Therefore, this schematic view might not be in scale for some specific showers.

the air shower propagate down to the ground and penetrate the surface detectors of the Pierre Auger Observatory.

The analysis procedures developed by the Pierre Auger Collaboration start from the signal measured as a function of time at each station, reconstruct the main properties of the shower, find the direction and energy of the primary particle and trace it back to its possible source in the sky. The actual reconstruction procedure used by the Pierre Auger Collaboration is complicated due to several details considered in the analysis [12]. The general idea is discussed below.

The stations used by the Pierre Auger Observatory (figure 2) are filled with water and have three photo-sensors (photomultipliers) looking downwards inside the water. The particles of the shower cross the station and produce a light flash inside the water. This phenomenon is called the Cherenkov effect. The light flash is detected by the three photo-sensors and sent to a data acquisition system. The measured signal of each station is, therefore, the total amount of light produced by the passage of the particles through the station.

If a high-energy primary particle with energy around 10^{20} eV produces a shower in the atmosphere, the number of particles reaching the ground is larger than 10^{10}. Conservation of energy and momentum in the particle interactions guarantees that the sum of the energy and momentum of all particles produced in the shower is equal to the energy and momentum of the primary particle. For the same reasons, the trajectory of the centre of mass of the shower is the trajectory the primary particle would have described if it had not interacted.

The phenomenon has an analogy in the classical problem of a projectile with a given trajectory which explodes during flight into several pieces. The trajectory of the centre of mass of the pieces is the trajectory the projectile would have followed had it not exploded. The hadronic and electromagnetic interactions that govern the development of the shower are fundamentally different from the chemical reactions and collisions involved in the explosion of a projectile. However, the analogy is valid because the relevant aspects, energy and momentum conservation, are valid in both cases. On the other hand, the explanation of the shower development offers an opportunity to discuss modern and contemporary concepts in the context of particle physics if the level of the students is appropriate. We discuss this possibility below.

The Pierre Auger Observatory surface detectors measure a sample of the particles in the shower. Due to the large number of particles in the shower the distribution of particles on the ground is to a very good approximation uniform. Therefore, the sample measured by the surface detectors is a good representation of the shower.

Figure 4 shows an example of an event measured by the surface detectors. The centre of each circle (black dot) is the position of a station and the radius of the circle (blue circle) is proportional to the logarithm of the signal detected by the station. We have plotted the radius proportional to the logarithm of the signal for clarity. The logarithm of the signal is not used in any of the following calculations.

The signal measured by each station is proportional to the total energy of the particles that crossed the detector. The Pierre Auger Collaboration uses a unit named VEM (vertical equivalent muon) to quantify the signal measured

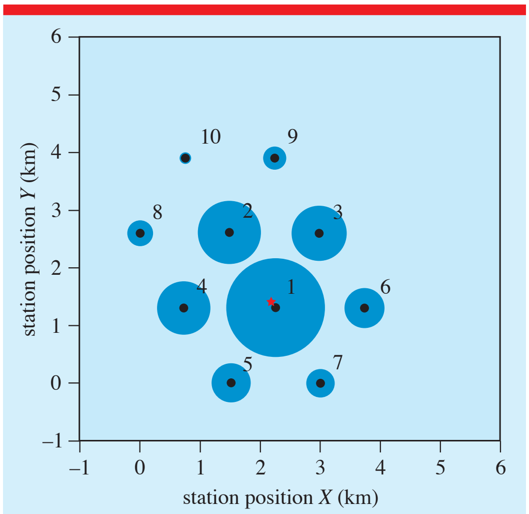

Figure 4. Schematic representation of the positions of the stations hit by a shower and their corresponding signals (see text). The detectors are numbered according to table 1.

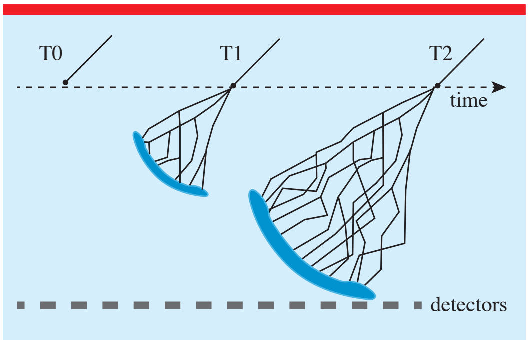

Figure 5. Shower development. The figure shows one air shower in three different development stages. The black boxes represent the detectors of the Pierre Auger Observatory. The blue area represents the spread of the particles in the shower front. Not to scale.

in one station. Therefore, the signal left by shower particles traversing the station is expressed in multiples of the intensity of the signal left by a single muon crossing the station vertically. The details of the signal measurement are not relevant to completion of the experiment proposed here. However, the explanation of the VEM unit allows us to discuss the existence of different particles beyond electrons, protons and neutrons.

The fundamental understanding required to continue the learning activity is that the signal measured by each detector is a measurement of the energy of all particles that impinged the detector. If that is achieved, following the argument above, the centre of mass of the detectors with weight given by the signal is the point where the primary particle would have hit if it had not interacted. The hit point is usually named the core position.

Returning to the analogy of the projectile trajectory, the detector diagram shown in figure 4 can be reinterpreted. In the analogy, the mass of each piece is the signal measured by each detector. Therefore the projectile (primary particle) would be at the centre of mass of the pieces (particles in the detectors) had it not exploded.

Particles in the shower propagate with a speed very close to the speed of light in vacuum. The propagation of the shower in the atmosphere is illustrated in figure 5. At a given time, the particles in the shower are distributed along a thin front travelling at almost the speed of light.

Figure 5 represents the shower development at three instants: T0, T1 and T2. At T0, the primary particle is shown entering Earth's atmosphere. At T1, the primary particle has already interacted and a shower is developing. The blue area represents the shower front containing all particles at instant T1. The shower front width is exaggerated for clarity. The shower front propagates with the speed of the particles, which is very close to the speed of light in vacuum. At T2, the shower has developed until it has reached the ground. Note that the detector on the right side has been hit by particles, while the detector on the left side has not been hit yet. The sequence of detector hits depends on the direction of the primary particle, as seen in figure 6. Therefore, the time pattern of the detectors on the ground is determined by the direction of the primary particle. Or, the other way around, it is possible to calculate the direction of the primary particle by measuring the time at which each detector was hit by the shower front.

The propagation of the shower front can be modelled as a section of a sphere expanding with almost the speed of light, again equivalent to a projectile explosion. Since the radius of curvature of this sphere is very large (several kilometres) a small section of the sphere front

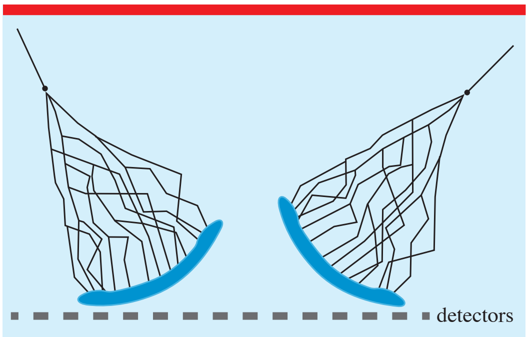

Figure 6. Shower development. Two showers are shown, each shower coming from a different direction. The figure illustrates how different shower directions generate different hit time patterns on the surface detectors.

Table 1. An event measured by the Pierre Auger Observatory. The table shows the number of the detector, its position, the measured signal and the time the detector was hit.

Station	X (km)	Y (km)	Signal (VEM)	Time (μs)
1	2.25	1.31	2184.7	1.62
2	1.49	2.61	129.0	2.41
3	2.99	2.60	71.8	0.56
4	0.74	1.31	65.4	3.96
5	1.52	0.01	23.2	3.39
6	3.73	1.31	23.1	0
7	3	0	9.3	1.64
8	0	2.61	7.4	4.95
9	2.24	3.90	6.4	1.69
10	0.75	3.91	2.7	4.69

can be approximated by a plane. The equation of motion of a plane with constant speed is

$$\sum_i \vec{n} \cdot \vec{r}_i = ct_i - k, \qquad (1)$$

where $\vec{n}$ is the vector normal to the plane, $\vec{r}_i$ is a position in space, t_i is the time the plane hit $\vec{r}_i$ and k is an arbitrary constant that gives the distance of the plane from the origin of the coordinate system at time zero. The plane is defined by its normal vector ($\vec{n}$), which is, indeed, given energy and momentum conservation, the direction of the primary particle.

This equation can be deduced from basic geometry; however, it is not needed for the development of the activity proposed here. What is stated in equation (1) is that a plane propagating with speed c hits the position $\vec{r}_i$ at time t_i. In other words, there is only one possible plane through the given positions r_i of the stations that were hit at given times t_i. Or even, if you know at least four points $\vec{r}_i$ in space where the unknown plane passed in time t_i you can calculate the direction perpendicular to the plane $\vec{n}$. The meaning of this equation can be discussed with the projectile explosion analogy once again.

The discussion above based on propagation and centre of mass allows one to calculate the impact point and direction of the primary particle and therefore it is possible to point out where in the sky the cosmic ray came from if the exact time at which the shower was measured is known. Fortunately, the local time (day, hour, minute and second) at which each shower as detected is also provided by the Pierre Auger Observatory. Knowing the position on Earth (latitude and longitude) of the Pierre Auger Observatory and the time of the event, it is possible to print the sky map of that instant using computer software. After calculating the direction of the particle and using software to image the sky above the observatory at that time it is possible to point out on the sky map where the particle came from. The determined direction is not very precise due to the approximations explained above and to the error in measuring the angles of the shower axis.

Description of the activity

The experiment proposed here is a way to reconstruct an event measured by the Pierre Auger Observatory by hand. The activity has been designed to be inexpensive so as to guarantee easy reproducibility. It is divided into three main steps: (a) reconstruction of the impact point, (b) reconstruction of the direction of the primary particle and (c) pointing out in the sky where the cosmic ray came from.

The experiment starts by drawing figure 4 from table 1. This table shows (a) the position of the station on the ground, (b) the time and (c) the signal measured when a shower hits the station. The positions of the stations have been shifted using one station as an arbitrary reference. The times have been shifted using the earliest time as a reference. Up to 24 January 2012, the Pierre Auger Observatory released 24 654 events like the one shown here.

Table 1 allows us to reconstruct the impact point directly by calculating the centre of mass using the equations

$$X_{\mathrm{cm}} = \frac{\sum_{i=1}^{N} X_i S_i}{\sum_{i=1}^{N} S_i}, \qquad (2)$$

$$Y_{\mathrm{cm}} = \frac{\sum_{i=1}^{N} Y_i S_i}{\sum_{i=1}^{N} S_i}, \qquad (3)$$

where X_i and Y_i are the positions of the stations and S_i is the signal measured. The result of the calculation for this event is $X_{\mathrm{cm}} = 2.19$ km and $Y_{\mathrm{cm}} = 1.4$ km. This point is marked with a red star in figure 4.

The second step is to reconstruct the direction of the primary particle. The student is directed to cut wood sticks with sizes proportional to the time each station was hit. The sticks are fixed on each station. This was achieved in our case by placing 3 cm of styrofoam under the paper on which figure 4 had been printed.

The size of the wood sticks has to be calculated in order to keep the space and time correspondence. The plane propagates with the speed of light so one has to use the same scaling used to draw the stations to calculate the size of the wood sticks. The real distance between the surface detectors is 1.5 km. If in the paper model the distance between the detectors is 5 cm, for example, that means that 1 cm in the model represents 300 m in reality. The model has a scale of 1/30 000 for the spatial coordinates. The same scale has to be used in the time domain. In this example, the light takes 1 μs to travel 300 m. Therefore, 1 cm of wood stick corresponds to 1 μs. In this way the time scale is set to be 1 cm of wood stick is equal to 1 μs. This scale is used to fix the size of the wood stick for each surface detector according to table 1. The time and space scales have to be calculated according to the size of the paper and sticks available to perform the experiment.

In order to have a very accurate reconstruction of the shower direction the wood sticks should be placed inclined in relation to the vertical. The inclination of the stick is needed because the time differences between stations are the distances perpendicular to the wave front. However, to have such a accurate procedure the student would have to know the direction of the shower beforehand and the activity would lose its meaning. We suggest here an approximation that allows reconstruction of the direction with small errors. If the sticks are fixed in the vertical there is no need to know the direction of the shower beforehand. This corresponds to a small angle approximation, in other words, a shower arriving on Earth close to the vertical can be reconstructed by this approach with a small error. Showers that are inclined in relation to the vertical would have larger errors. This should be taken into account when choosing the event from the Pierre Auger database[2]. By choosing events with zenith angle smaller than 45° one limits the error of the reconstructed direction to less than 20%.

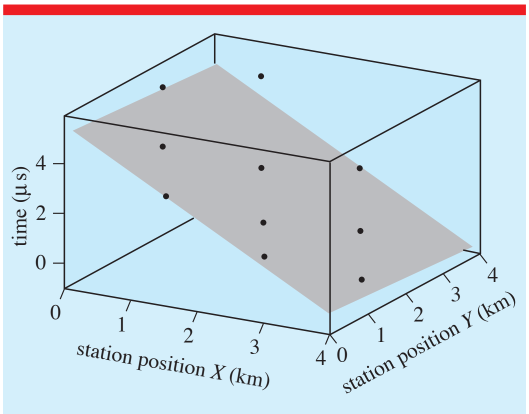

Figure 7. Illustration of the shower front. The figure shows the time and position of each hit tank (black points). The grey plane is the best fit plane to the data points.

After the sticks are fixed, it becomes clear that their ends lie on a plane, which is the shower front. Figure 7 shows a plot of what the result of the model should be. The plot shows on the XY plane the position of the station. In the third coordinate we plot the time the station was hit. This is exactly what was carried out in the experiment. Figure 7 also shows a plane fitted to the time delay that illustrates the shower front. The shower front is going to be constructed in the experiment as described below.

The primary particle direction is the direction perpendicular to the shower front. The shower front can be approximated by a plane which can be better identified by laying a sheet of paper or a

[2] http://auger.colostate.edu/ED/.

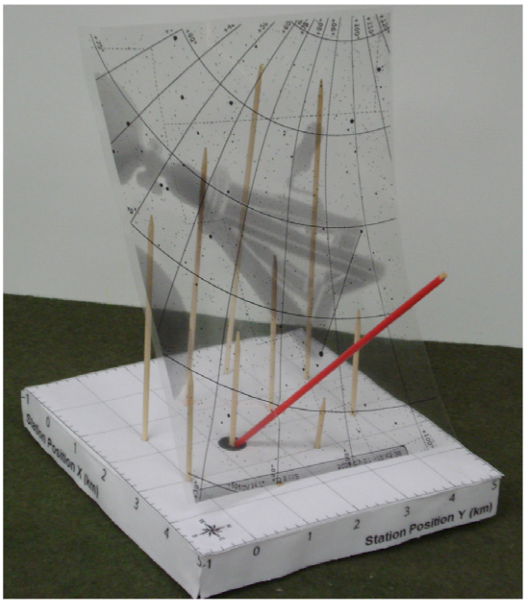

Figure 8. Picture of the model.

slide on top of the sticks. At the end of this step, the student can identify the path of the primary particle by placing a stick at the impact point which is perpendicular to the plane of the shower front. See figure 8. The direction of the primary particle is shown by the red stick.

In events where many stations were hit it is possible to see a curvature of the paper or slide on top of the sticks which resembles the curved shower front.

In the experiment the student can measure the angle between the red stick and the ground, which is the altitude/elevation. It is also easy to project the red stick on the ground and measure the angle between the projection and north, which is the azimuth. Using the azimuth, altitude, latitude (35.3°S) and longitude (69.3°) of the Pierre Auger Observatory and the time of the event it is possible to print a sky map of that moment. Figure 8 shows the sky map from the Stellarium[3] computer program printed on a slide.

In order to be very precise, the exact geographic position of each station is used in the official analysis of the Pierre Auger Observatory. However, the error in using the geographic location of the centre of the observatory (latitude 35.3°S and longitude 69.3°) is very small (a tenth of a degree) and is not relevant for the conclusion of the activity.

Discussion

The activity proposed here allows the discussion of several concepts, which are listed below. The discussion is presented according to the steps needed in the construction of the experiment.

Impact point reconstruction

The reconstruction of the impact point is based on the concept of centre of mass. The use of the mathematical formalism, equation (2), is not difficult to explain in the standard way and the analogy with the projectile explosion is very useful to connect the knowledge. However, these steps present other difficulties and opportunities such as scaling, area and coordinate representations.

Arrival direction

The arrival direction of the primary particle is based on the time of flight of the particles. This is probably the easiest step in the construction of the activity, but nevertheless it is an important pedagogical tool. The teacher can work out time differences between the stations and propagation in three dimensions. An understanding of the propagation of an extended object (plane) in three dimensions is implicit in this step. It is also possible to work the concept of scales in space and time. The construction of the model shown in figure 8 is a representation of this propagation. Therefore, this step of the experiment transforms a complicated mental image into a real model.

Sky map

The construction of the sky map is a step that depends on geo-orientation in order to orient the observatory on Earth in space and the event in time. First, the students have to understand the orientation of the array of stations on Earth which is given by the printed compass shown in figure 8. Then, the students have to understand that the experiment is rotating together with the Earth around its axis and around the Sun.

[3] Stellarium is a free open source planetarium for your computer: www.stellarium.org.

Therefore, the red stick shown in figure 8 is at each moment pointing in a different direction in the sky. Knowledge of the exact time at which the event arrived is the only way to determine the real direction in the sky that the cosmic ray came from.

Particle physics

A knowledge of particle physics is completely avoidable for successful completion of the experiment. The same activity could have been carried out using the projectile analogy. However, the fact that this is a physics problem extracted from a real observatory in operation allows the teacher to explain basic modern physics concepts.

- The shower development can be used to explore the existence of other particles besides electrons, neutrons and protons.
- The transformation of types of particles can be used to explore the relation between mass and energy.
- The very high-energy particle (10^{20} eV) measured by the Pierre Auger Observatory can be used to discuss energy scales. These particles are microscopic bodies carrying macroscopic energies.
- The creation of a jet of particles can be used to link astroparticle physics to accelerator experiments.

Final remarks

This paper presents an activity in astroparticle physics that can be completed by high-school students. The activity exploits the public data set from the Pierre Auger Observatory.

The experiment allows students to reconstruct the arrival direction of a cosmic ray particle measured by the observatory using simple concepts in classical physics. At the same time, the experiment allows the teacher to discuss modern and contemporary theories of physics. During the preparation and execution of this activity the teacher has an opportunity to discuss classical subjects like centre of mass and trajectories as well as modern subjects such as particle physics and the structure of matter.

The association of ideas going from classical to modern physics, from subjects traditionally discussed in the classroom to measured data of a modern observatory, from microscopic structures (particles) to macroscopic scales (galaxies, the sky) is one of the characteristics of the activity proposed here which has already been shown to bring permanent knowledge to high-school students according to preliminary tests we have carried out in the classroom.

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