Letter of intent to the Pierre Auger Collaboration

A detailed characterization of the atmospheric aerosols and precursors at the Pierre Auger Observatory

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Objectives

The Pierre Auger Observatory has developed during the last years a large program to monitor the atmospheric aerosols. We propose to extend this monitoring program with the installation of several facilities to improve our knowledge about aerosols. In fact, some studies done in the collaboration have highlighted possible systematic errors coming from the aerosol size or some trace gases. The goal of this project is hybrid: for the Pierre Auger Collaboration, a better knowledge of the atmospheric aerosols and the pollutants, and for our groups, specific studies to better understand the link between aerosols and climate evolution.

Introduction

This letter of intent is in the context of the public conference IS@AO where interdisciplinary science at the Pierre Auger Observatory was discussed [1]. One year ago, a group from the LISA laboratory contributed to the conference by presenting some ideas for a collaborative project between the Pierre Auger Collaboration and the french community of atmospheric sciences in France. Since this workshop, this project grew up and it is the purpose of this letter of intent. Now, in collaboration with a second group, the LaMP/OPGC laboratory, we would like to install some facilities on the Pierre Auger site to develop our studies in atmospheric sciences. In this project, the LPSC group, member of the Pierre Auger Collaboration, will be the intermediary between us and the collaboration.

1 Atmospheric sciences at the Pierre Auger Observatory

The Pierre Auger Observatory [2, 3] is the largest operating cosmic ray observatory ever built. It has been conceived to measure flux, arrival direction distribution and mass composition of cosmic rays from 10^{18} eV to the very highest energies. It is located in the "Pampa Amarilla" site ($35.1^\circ - 35.5^\circ$ **S**, $69.0^\circ - 69.6^\circ$ **W**, and $1300 - 1400$ m above sea level), close to Malargüe, Province of Mendoza, Argentina. The atmosphere is used as a giant calorimeter, representing a detector volume larger than 30 000 km^3. Once cosmic rays enter into the atmosphere, they induce extensive air showers composed of secondary particles. Charged particles excite atmospheric nitrogen molecules, and these molecules then emit fluorescence light in the $300 - 400$ nm range. The number of fluorescence photons produced is proportional to the energy deposited in the atmosphere due to the electromagnetic energy losses undergone by the charged particles. The production rate of fluorescence photons depends on the temperature, pressure and humidity of the air. Then, from their production point to the telescope, photons can be scattered by molecules (*Rayleigh scattering*) and/or atmospheric aerosols (*Mie scattering*) .

Thus, to minimize as much as possible the systematic errors on the fluorescence measurements, the atmosphere properties have to be continuously monitored. An extensive and unique atmospheric monitoring system has been developed covering the whole observatory [4]. Figure 1 lists the different experimental facilities and their locations. The state variables of the atmosphere are recorded at ground level using five weather stations. Above the Pierre Auger Observatory, the height-dependent profiles have been measured using meteorological radio-sondes. Aerosol monitoring is performed using two central lasers (CLF / XLF), four elastic scattering lidar stations, two aerosol phase function monitors (APF) and two optical telescopes (HAM / FRAM). Also, a Raman lidar currently tested in Colorado (USA) is scheduled to be moved to the Auger Observatory for the Super-Test-Beam project [6]. For cloud detection, an infrared cloud camera is installed on the roof of each fluorescence station.

1.1 Atmospheric aerosols and some remaining questions

Although atmosphere is mainly composed of molecules, a small fraction of larger particles such as dust or droplets are in suspension. These particles are called *atmospheric aerosols* and their typical size varies from a few nanometres to a few microns. Most of the atmospheric aerosols are present only in the first few kilometres above the ground level. Unlike the molecular component, aerosol population is highly variable in time and location, depending on the wind and weather conditions. Also, they are highly mobile.

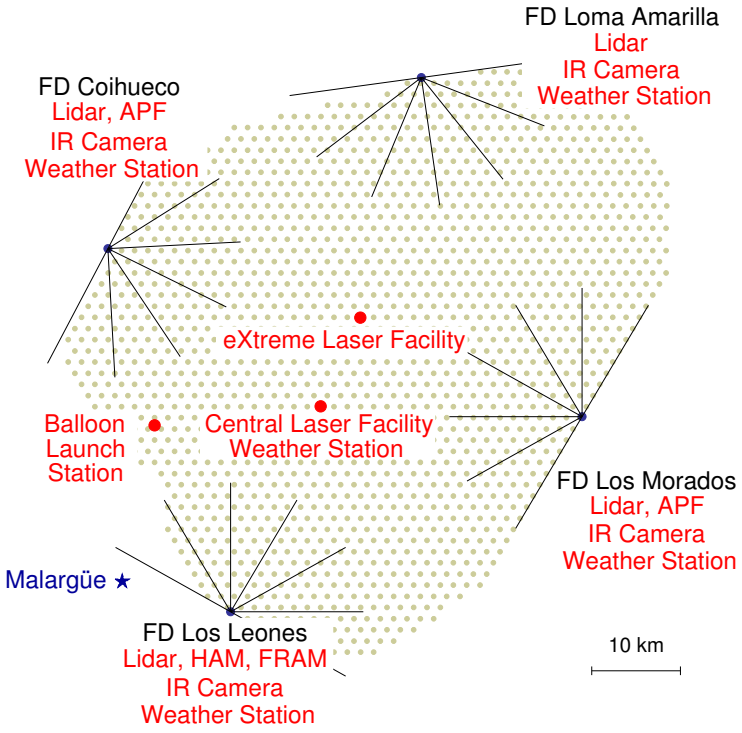

Figure 1: **Atmospheric monitoring map of the Pierre Auger Observatory (from [5]).** Grey dots show the positions of surface detector stations. Black segments indicate the fields of view of the fluorescence detectors (FD) which are located in four buildings on the perimeter of the surface array. Each FD site hosts several atmospheric monitoring facilities.

The contribution of the scattering effect has to be well estimated for precise shower reconstruction. Multiple scattering (MS) increases the amount of light arriving at the detector from the source. A significant study concerning the aerosol effects has already been done in [7] by modifying the aerosol vertical scale H_a and the aerosol attenuation length Λ_a. But, the dependence of the MS on the aerosol phase function P_a (i.e. the aerosol size and the aerosol shape) has to be also considered as explained in [8]. The Auger Collaboration parameterizes the aerosol phase function by the Henyey-Greenstein function $P_a(\zeta, g_{HG})$, where ζ is the scattering angle and $g_{HG} = \langle \cos\zeta \rangle$ is the asymmetry parameter [9]. Figure 2 shows FD camera displays for observing an isotropic point source, located 15 km away from the FD telescope and at an elevation angle[a] of 19.2°, for two aerosol conditions: dominated by very small aerosols on the left, and by large aerosols on the right. These two displays show a clear effect of the APF on the multiple scattering signal.

Up to now, the Auger Collaboration monitors only the aerosol optical depth and fixes the aerosol phase function (by an asymmetric parameter g_{HG} constant). A better understanding of the aerosol effect could be reached by getting aerosol size distribution and aerosol shape *in situ* at the Pierre Auger Observatory. Using these two quantities, it would be possible to provide to the Offline a more realistic aerosol phase function.

[a] These two values represent the typical location of the shower maximum for an energy around $10^{18.6}$ eV.

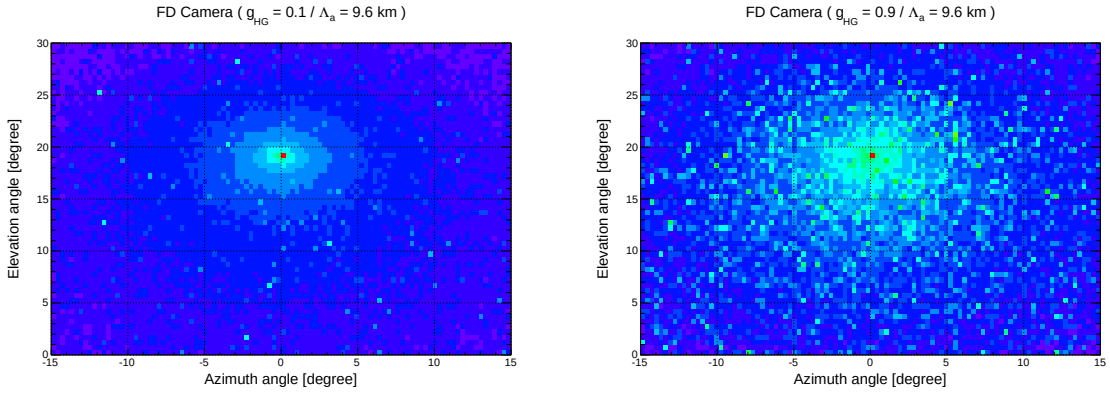

Figure 2: **FD camera displays for two different aerosol conditions.** *Left panel*: Mean aerosol size around 0.2 µm ($g_{\mathrm{HG}} = 0.1$). *Right panel*: Mean aerosol size around 2.0 µm ($g_{\mathrm{HG}} = 0.9$). The light source is located 15 km away from the FD telescope, and at an elevation angle of 19.2°.

1.2 Ultraviolet and visible absorption by atmospheric trace gases

The atmosphere is not only composed of the "permanent gases", corresponding to the molecular part, and of the aerosols. Water vapour H_2O has to be considered and may account for up to 4% of the atmospheric gases in some temperature conditions. Then, several "variable gases" are present in a very small quantity in the atmosphere. Among them, the main gases are carbon oxides CO and CO_2, methane CH_4, ozone O_3, nitrogen oxides NO and NO_2, or sulfur dioxides SO_2. To these components, we have to add also the Volatile Organic Compounds (VOCs) which are a class of organic compounds, most of them being hydrocarbons.

These atmospheric trace gases come from both *natural sources* and *human activities*. Examples of natural sources include wind picking up dust and soot from the Earth's surface and carrying it aloft, volcanoes belching tons of ash and dust into our atmosphere, or forest fires producing vast quantities of drifting smoke. As human-induced sources, one cites usually transportation, fuel combustion or industrial processes. These different gases had previously constant concentration in the atmosphere, since their origin was exclusively natural. But, nowadays, human activities increase the concentrations of these gases called as air pollutants.

In the case of the Pierre Auger experiment, the spectral range probed is centred around 350 nm. In this spectral range, the photoabsorption is mainly caused by ozone O_3, nitrogen dioxide NO_2, sulfur dioxide SO_2 and nitric acid HNO_3.

1. At the surface, **ozone O_3** is the primary ingredient of the *photochemical smog*[b]. Even if the majority of atmospheric ozone (about 97%) is found in the upper atmosphere – in the stratosphere – where it is produced naturally, approximately 0.04 ppm (parts per million) is present in the low part of the atmosphere.

2. The **sulfur dioxide SO_2** is a colourless gas coming primarily from the burning of sulfur-containing fossil fuels (such as coil or oil). However, it can enter the atmosphere naturally during volcanic eruptions and as sulfate particles from ocean spray. As it is known, the region where the Pierre Auger Observatory is installed is affected by air masses coming from the Pacific Ocean, and is a active volcanic region.

[b]The word *smog*, originally meant the combining of smoke and fog. Nowadays, it mainly refers to the type of smog that forms in large cities where, with the presence of sunlight, occur chemical reactions.

Atmospheric gas	Cross section at 350 nm [cm^2]	Concentration [$\mu g/m^3$]	Λ_{abs} [km]
Ozone O_3	2×10^{-22} [10]	80 µg/m3 [14]	50 000
Nitrogen dioxide NO_2	4×10^{-19} [11]	30 µg/m3 [15]	64
Sulfur dioxide SO_2	8×10^{-23} [12]	8 µg/m3 [16]	2×10^6
Nitric acid HNO_3	1×10^{-24} [13]	2 µg/m3 [17]	5×10^8

Table 1: **List of the most efficient absorbers around 350 nm.** Their concentration in the low part of the atmosphere, and their corresponding photoabsorption cross section are given for each atmospheric gas. Λ_{abs} is the attenuation length.

3. The **nitrogen dioxide NO_2** is a gas that forms when some of the nitrogen in the air reacts with oxygen during the high-temperature combustion of fuel. Although it is produced naturally, its concentration in urban environments is 10 to 100 times greater than in nonurban regions. In moist air, nitrogen dioxide reacts with water vapour to form corrosive **nitric acid HNO_3**, a substance that adds to the problem of acid rain.

Table 1 gives the photoabsorption cross section and the concentration at ground for the four species just enumerated previously. The cross sections are given for ambient temperature, at a pressure of one atmosphere. Then, for each gas, the equivalent attenuation lengths are calculated. Thus, whereas ozone, sulfur dioxide and nitric acid have attenuation lengths very large compared to the Rayleigh or Mie scattering processes, nitrogen dioxide, due to a large cross section, gets an attenuation length around 60 km. Such a value cannot be neglected in light attenuation studies at the Pierre Auger Observatory.

Hence, it could be interesting to consider a monitoring of the NO_2 concentrations above the Auger array. The NO_2 concentrations should be affected by the air masses travelling through the Pierre Auger Observatory, as it is already the case for the aerosol population. Since the Auger observatory is located in a nonurban region, the NO_2 concentrations are probably relatively low. But some nights would be affected by the NO_2 absorption when, for instance, the air masses have previously travelled cities. If such a monitoring can be undertaken, it could be useful to measure other species concentrations as ozone O_3, oxygen dimer O_4, bromine monoxide BrO or chlorine dioxide OClO, since their photoabsorption cross sections are of the same order of the nitrogen dioxide one [18].

2 Presentation of the projects

This letter of intent can be divided into two main projects, each of them proposed by one group. Nevertheless, for the Pierre Auger Collaboration, it represents only one goal: a better understanding of the atmosphere properties, to reduce the systematic uncertainties on the air shower reconstruction.

2.1 Modelling of the evolution of aerosols in South America (LISA's project)

Atmospheric dust is one of the major vectors feeding open ocean surface waters with trace metals [21]. Even at extremely low concentrations, trace metals are micro nutrients necessary for the growth of phytoplankton [22]. By this way, the trace metals are linked to climate since they affect the capability of the marine biomass to trap CO_2 [23].

The Austral region ranging from about 40° and 65° south is one of the major CO_2 sink. This region is also very remote from continents and thus atmospheric dust exhibits very

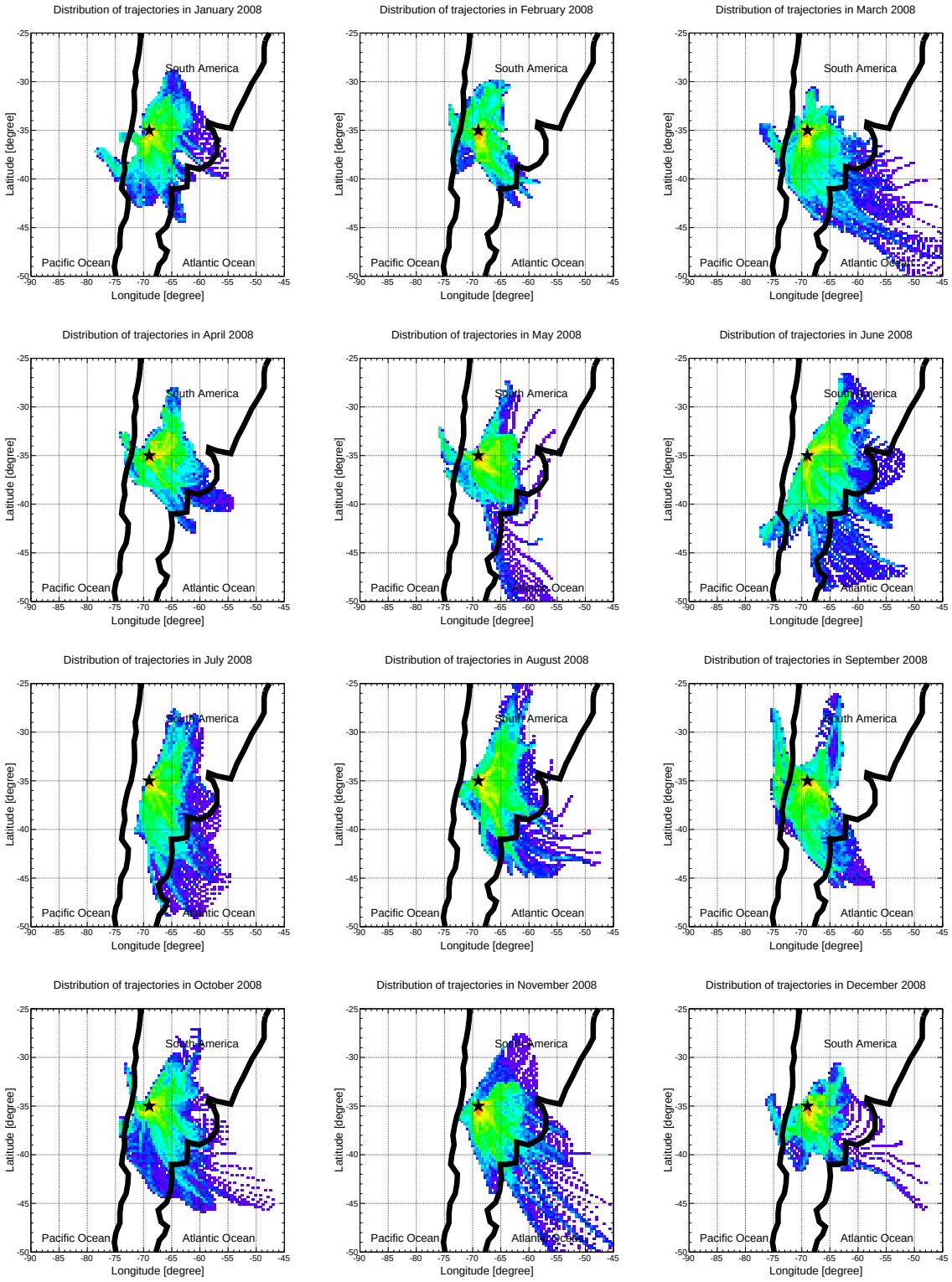

Figure 3: **Distributions of monthly 48-h forward trajectories from the Malargüe location.** Paths estimated with HYSPLIT [19, 20] for the year 2008, for a start height AGL fixed at 500 m. The black star represents the Auger location. The black line represents the coasts. The colour indicates the frequency of a region, from blue to red.

low concentrations [24–27]. This oceanic area is a HNLC region (High-Nutrients Low-Chlorophyll) and dust deposition could be a severe limiting factor for the primary production [28, 29]. These authors stated from modelling studies that the primary productivity is proportional to the aeolian dissolved iron deposition originated from dust. Iron bioavailability, and those of other nutrients, is conditioned by the ability of mineral dust to be dissolved in seawater. In the current estimation of atmospheric dissolved iron fluxes, solubility of atmospheric iron in seawater remains a major source of uncertainty [30]. Fluxes are generally calculated with an average solubility value obtained from available data in literature [27, 28]. Yet the large majority of data are related to African and Asian dust. Given the key role of the Austral Ocean on global climate, it is required to initiate studies that aimed to characterize iron and other trace metal solubility from Patagonian and more generally South America dust. We know at the moment that solubility is strongly linked to the mineralogy of the source aerosol [31, 32]. The chemical properties of the source aerosol is therefore of primary importance to be documented.

Because the South Hemisphere is mainly constituted of oceans, the only possible dust sources are, Argentina, South Africa and Australia. Argentina and especially Patagonia is suspected to be the major dust source for the oceanic region ranging between 40° S and 60° S. To illustrate this purpose, distributions of monthly 48-h forward trajectories from the Malargüe location, using the HYSPLIT tool, are represented in Figure 3. A project, funded by the French Research Council CNRS (INSU/LEFE: "Dust from Patagonia"), started in January 2012 for 3 years targeting South Patagonia.

We aim to improve our knowledge of the emitted dust by characterizing the aerosol emitted from the regions situated East from Andes, where the Auger Observatory represents a good opportunity because of the existing scientific background installed and lidar equipment. Without airplanes, aerosol sampling take place at ground level and lidar will bring knowledge of the vertical distribution of the dust. The general and local atmospheric circulation can transport dust layer at high altitude without connection to the ground, or do not transport any dust over long distances because dust remains very close to the ground level. Lidar profiles will identify emission episodes on a large vertical scale and let evaluate if collected aerosol at ground level extends to higher altitudes to be long range transported.

In a close collaboration with M.I. Micheletti, member of the Pierre Auger Collaboration, we propose to collect aerosols and make chemical measurements including iron solubility. These measurements will be also useful for optical purpose because iron is one of the major chemical elements which can give light absorption by aerosol rather than simple diffusion.

2.2 Link between ionic precursors, aerosols and cosmic rays (LaMP's project)

Aerosols play a major role in climate directly by absorbing and scattering the solar and telluric radiation but also by acting as cloud condensation nuclei (CCN) and modifying the cloud properties. The aerosol properties that are relevant in climate issues are their *number*, *size* and *chemical composition*.

LaMP has been involved in many long term studies of aerosols physical and chemical properties at atmospheric observatories representative of background conditions (France, Switzerland, Nepal, Japan) [36–41]. These studies indicate that the number, size and composition of aerosol particles show clear seasonal and diurnal variations in remote environments, that are a function of both their sources (air mass origin and pathways) and the atmospheric dynamics (boundary layer height). In all environments, the physico-chemical characteristics of aerosols could be described as a function of these parameters. In order to better understand the aerosol sources, a particular emphasis was put on the study of new particle formation processes, i.e. on the formation of nanoparticles from gaseous molecules/ions by

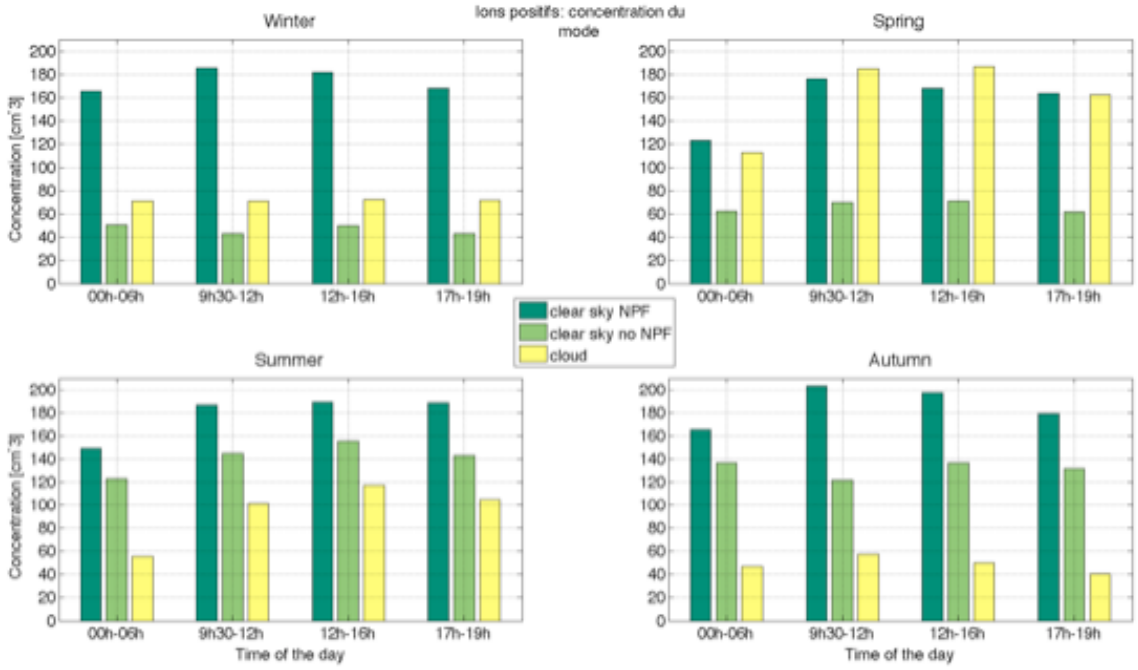

Figure 4: **Median cluster ion concentrations (particle diameter $D_p < 1.2$ nm) as a function of the time, of the day and season measured at the Puy de Dôme station for the period 2006-2011 for new particle formation event days (NPF) and no NPF days under clear sky conditions.**

nucleation. New particle formation involves high concentrations of low vapour pressure gases and low concentrations of pre-existing particles and may be favoured by the presence of charges/ions. The influence of the presence of ions on the formation of new particle is one major focus of the CLOUD experiment, at CERN. In the aim of studying the role of ions on the formation of new particles in the real atmosphere, several studies have also monitored ion concentrations using ion spectrometers (NAIS). LaMP has studied the seasonal variation and air mass dependency of such ions at several sites [39, 42, 43]. The results show that the cluster ion concentrations are larger on nucleation days compared to non-nucleation days (see Figure 4). However, the dominant sources of ions in the real atmosphere are not unambiguously identified, and the influence of galactic cosmic rays (GCR) on these concentrations were, to our knowledge, not yet measured at ground-based observatories.

An indirect estimation of the GCR flux is provided by the Pierre Auger Observatory using the surface detectors [44]. It consists of measuring the low threshold rates (or *scalers*) of the surface detectors. Scaler rates are influenced by the GCR flux, atmospheric conditions (mainly pressure) and instrumental instabilities (here this effect is not correct and assumed to be negligible). In Figure 5(a) is represented the daily variation of the averaged scaler rate for the year 2011. After having corrected it of the atmospheric pressure, a slight solar modulation remains with a maximum around 14-h in local time. The evolution of the scaler rate since 2006 is shown in Figure 5(b), compared to the sunspot number[c]. The long-term modulation, associated to the solar cycle, is depicted by the averaged scaler rate: a maximum is measured by the surface detectors when the number of sunspots is close to zero. Even if it seems possible to measure indirectly the GCR flux at the Pierre Auger Observatory, some

[c]The sunspot number indicates the solar activity. A sunspot number equal to zero means that there were no visible sunspots on that date.

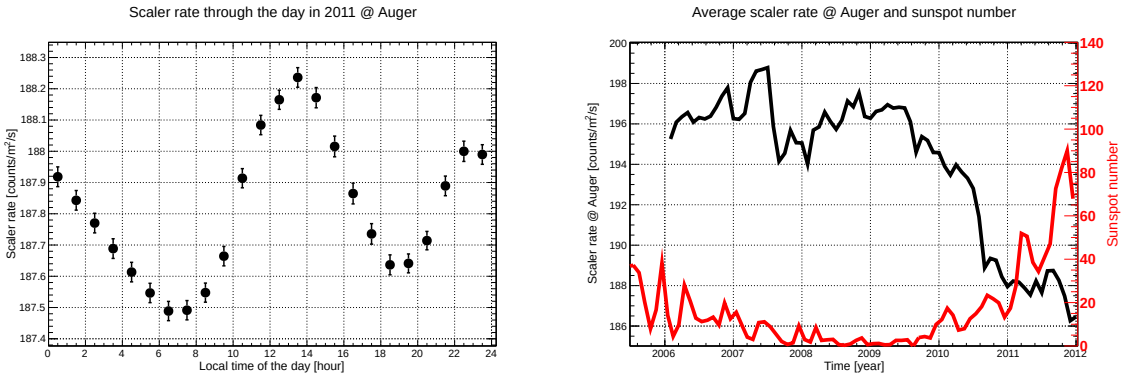

Figure 5: **Averaged scaler rates measured at the Pierre Auger Observatory.** (a) Daily variation of the averaged scaler rate, corrected of the pressure, for the year 2011. (b) Evolution of the averaged scaler rate since January 2006. It is compared to the sunspot number, an indicator of the solar activity [45].

improvements have to be performed to reduce systematic uncertainties if we want to use them for long-term studies. One idea, suggested by Xavier Bertou, could be by using the histograms of muons measured in each surface detector for their VEM calibration.

One major objective of the collaboration between LaMP and the Auger Collaboration would be to study the relationship between GCR and the formation of new particles by nucleation. Cluster ions could be related to GCR measured at the observatory, for the first time to our knowledge. In order to understand the ion concentrations, other sources (radon), condensing species that make the ions detectable at 0.4 nm (SO_2 and VOCs) and sink (pre-existing particle) should be measured. A project called *Bicycl'Air*, conducted from December 2005 to March 2006, reported first concentrations of VOCs in the Andes mountains, and especially in Santiago del Chile. 120 air samples were taken in Chile and Argentina at different latitudes, altitudes and sites [47].

Method: Neutral Air Ion Spectrometer (NAIS) and Scanning Mobility Particle Sizer (SMPS) should be monitored continuously to provide the ion and particle size distribution from 0.4 nm to 800 nm, and SO_2 and VOCs. A project should be proposed to finance equipment and missions (100 keuros for the equipment, 30 keuros for travelling and shipping expenses) in case of long term measurements.

Other benefit for the Auger collaboration: The SMPS data can serve for calculating the optical properties of aerosols, maximum for the accumulation mode sizes (between 100 and 300 nm diameter) as calculated for the Puy de Dôme station [46]. Also, as explained in Section 1.2, some VOC measurements could explain the increase absorption of fluorescence light during its propagation to the the telescopes.

3 Initial phase for the project

Concerning dust, the first action should be an inventory of existing aerosol samples, and some field campaigns to complete the sample set. A pumping system could be installed at a selected area to collect aerosols on filters. Lidar would be operated as frequent as possible to retrieve the vertical shape of the aerosol layers.

Concerning nucleation and galactic cosmic rays, an AIS (for nanometric cluster particles) and VOC cartridges sampling could be installed for an intensive campaign of two–three months in order to investigate if a possible link between clusters and GCR exists.

4 Benefits for the Pierre Auger Collaboration

If these two projects can be performed during the next years at the Pierre Auger Observatory, several new facilities will be installed to better understand the atmospheric effects. For the atmospheric aerosols, their size, their shape or their chemical composition will be measured. Thus, it will be possible to take into account more accurately their effect on the air shower reconstruction. Also, it will be possible to answer some questions, as the absorption due to aerosols (and not only the scattering) or our assumption on the aerosol phase function.

The Pierre Auger Observatory is located in a region where only a few meteorological stations are installed. With these additional facilities to measure, for instance, the NO_2 concentration in the atmosphere, the Pierre Auger Observatory could be candidate to become member of international networks as the Global Atmosphere Watch (GAW) program. The GAW program of the World Meteorological Organization is a partnership involving eighty countries, providing atmospheric data to understand climate, weather and air pollution [48].

Acknowledgments

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