Moon based observation of cosmic rays

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***Abstract*- The 'Moon Base initiative' is presented and the possibility of using this opportunity for cosmic ray observations discussed. Several open questions could be afforded: (1) fluxes of heavy nuclei (up to actinides); (2) isotopes up to several tens GeV/nucleon; (3) rare components (antiproton and positrons, and hunting for antinuclei) up to the TeV region; (4) elemental composition up to 100 PeV (well beyond the knee); (5) UHECR up to a few ZeV. Furthermore an efficient UHE neutrino observatory can be conceived, capable of high statistics beyond 10^{20} eV, opening a new observation window to the astronomy. A few concepts of possible first generation Moon based detectors are described.**

I. Introduction

In most of the satellite borne CR experiments, as in general in all satellite borne experiments, the mass and cost of the spacecraft and of its services (altitude and attitude control, power generation and distribution, telemetry, etc.) largely exceed the mass and cost of the experimental device. This fact, as well the increasing concurrence by other field of the science and applications, greatly reduced in last two decades the number of flown satellite born cosmic ray experiments.

Of the many experiments envisaged in the CR program elaborated by NASA at the beginning of the 80s [1], only two main missions could be launched in space: the CR Isotope Spectrometer (CRIS) [2] on board of the Advanced Composition Explorer (ACE) in 1997 and, this year, the PAMELA [3] mission, heir of the WIZARD [4] experiment planned two decades ago for the ASTROMAG facility [5] of the never flown Freedom Space Station. The few other missions flown are several small telescopes dedicated to the study of Solar CR [NINA, NINA2] or to applied CR (Si-eye-1 and -2 on board of the MIR Station and Si-eye-3 on board of the ISS), and the AMS-1 [6] on board of the Shuttle, precursor of the still on stand-by AMS-2 experiment [7] planned for the ISS.

The projects ENTICE [8] and ECCO [9] (heritors of the Heavy Nuclei Collector (HNC) [10] planned on board of the Freedom SS) are so far not founded, and now hampered by the coming casting off of the Shuttle.

The cancellation of the ASTROMAG facility due to the freezing of the Freedom SS program in 1990 halted, besides to the above mentioned WIZARD, several other planned CR experiments, some of them in an advanced stage of development. It is worthwhile to remember the LISA [11] experiment, devoted to the study of the energy spectra of a large number of isotopes and rare components, the SCINATT-MAGIC [12] experiment, devoted to the study of the CR composition at the knee, the ASTROGAM [13] experiment, devoted to the high energy gamma ray astronomy beyond the limit reached by the EGRET [14] experiment on board of the CGRO observatory. The LISA experiment was conceived for continuing at higher energies the physics of CRIS on ACE but could never be re-proposed; the composition at knee, object of the SCINATT-MAGIC experiment, was re-proposed by the ACCESS [15] project, which however was never supported.

Also the missions, suggested in the original NASA program and studied in the meantime, dedicated to the measurement of the flux of CR in the extreme energy region, such as EUSO [16], OWL [17] and KLYPVE [18] cannot be still implemented, hampered by the shortage of occasions of flight and the required investments. To the study of the very high and ultra high energy CR are dedicated only two missions to be considered as precursor of bigger not founded missions, the NUCLEON [19] experiment around the knee region and the TUS [20] experiment for the extreme energy region, both flown as piggyback of Russian satellites.

II. The Moonbase Initiative

The establishment of a permanent base on the Moon in a not too far future will be an important opportunity for astronomical and astrophysics observations.

As matter of fact the possibility of installing CR experiments on an already organized and serviced lunar habitat can significantly reduce the required investment, as already proven for the many experiments performed on board of the MIR Space Station and of the ISS. This highly compensates for the cost of the Earth-Moon transportation, that in addition it is anticipated to decrease by a sensible factor in the next decade.

The location on the Moon offers several additional advantages, which are particularly attractive for CR physics [21]. The most relevant are:

- absence of a magnetic field: all the CR to reach the Moon surface;
- absence of an atmosphere: all CR reaching the Moon surface are primary;
- low gravity: advantage for supporting structure, but disadvantage for maintaining precise shapes of light large instruments (e.g. for inflatable optical elements).

As it was the case in the seventies for the Great Observatories (Hubble telescope, CGRO, AXAF, SIRF) in view of the shuttle operations, a complete program at the forefront of space science and technology should include a set of Moon based Observatories to explore any aspect of the Universe.

For expanding our knowledge to the extreme Universe at higher energies the Moon based CR observation must be part of this program.

The initiative of studying the possibility of concentrating several experiments in an organized and serviced ‘condominium’ on the Moon [22] was taken by a working group, promoted by High Frontier, Inc (USA) and the ‘Solidarietà e Sviluppo Association’ (Italy), representing professionals working in Research Centers and in Space Industries.

In 2003, a few months in advance of the USA President announcement (in January 14, 2004) of a major programme oriented towards the human exploration of the solar system using the Moon as a starting point, the Promoting Committee of the ‘MoonBase initiative’ set a program for deeply studying the argument, involving the main space agencies, in partnership with industries and scientific organizations. The program was implemented in different studies made public by the International Conference “Moon Base: A Challenge for Humanity”, realized by a series of dedicated workshops. The first workshop was held in Venice in May 2005, the second one in Washington in October 2005, and a third one will be held in Moscow in November 2006.

The USA Presidential Commission, set in January 2004 just after the USA President’s announcement, recommended in its final report [23] to engage the scientific community in a “*re-evaluation of priorities to exploit opportunities created by the space exploration vision*”. Endorsing this recommendation, beside the political and technical thematic, particular attention was given by the ‘MoonBase initiative’, to the possibility of using the Moon for scientific observations in astronomy and astrophysics. The electromagnetic component was treated in the Venice workshop by the director of the European Southern Observatory [24], while the possibilities offered for the study of the most relevant long standing problems in CR physics were discussed in the Washington workshop [25]. The conclusions of the Washington report are reproduced in fig.1.

High Z:	HNeXplorer (HNX) [exp. ENTICE + ECCO] in ’stand by’ possible only on the Moon surface
Isotopes (E>GeV/n):	on Earth orbit ≈80 are accessible but no plans exist light isotopes from BESS, PAMELA, AMS in next years high rate assured on the Moon up to very high E
Rare components:	antiN/N up to $<10^{-9}$ (AMS) antip, e+ up to a >200 GeV (PAMELA ed AMS) electrons up to >3 TeV (PAMELA, AMS, CALET) 1-10 TeV region on reach on the Moon surface
Elemental composition:	up to 100 TeV by ballooning (going on) up to 1 PeV in orbit (several projects and concepts) up to 100 PeV (well behind the knee) on the Moon
Ultra High Energies:	up to few * 100 EeV on Earth surface (going on) up to 1000 EeV from orbit (but EUSO in ‘stand by’) up to a few 10 ZeV from the Moon surface, a UHE Neutrino Observatory ($E_\nu > 10^{19}$) is feasible

Fig. 1 – Summary of possible achievement by future Moon based experiments (underlined rows).

III. First Generation CR Expt.’s on the Moon

Let in this work have a look to what can be achieved by a number of first generation experiments, i.e. by experiments based on today available experimental techniques that could be conducted from the very beginning of the Moon base operations on the Moon. Possible apparatuses will be briefly discussed for affording the physics problematic according to the scheme of fig.1.

A. Flux measurement of extreme Z cosmic rays.

The measurement of the fluxes of very high Z and extreme Z nuclei pursued by the above mentioned ENTICE and ECCO proposals can be performed by exposing on the Moon surface modules based on passive techniques, transported back to the Earth a few years later for their etching and analysis. The modules can consist of sandwiches of plastic and glass foils, as in the LDEF and MIR [26] precursor experiments, organized with already proved techniques for providing information on the registration time and temperature conditions event by event. Furthermore in the quasi-polar location presently foreseen for the possible Moon Base it can be find positions where the temperature range excursion can be compatible with the characteristics of the presently used materials. The dimensions of the modules can be chosen according to the convenience from a few tens cm^2 to one m^2, and their mass be less than 100 kg/m^2. With these dimensions and mass they can be transferred to the Moon and carried back as spare loads on the space of a long period of time, depending from the conveniences. By transferring to the Moon and back to Earth a few tons distributed on several year it will be possible to outclass the results foreseen for the above mentioned ENTICE and ECCO projects.

B. Energy spectra of isotopes and rare components.

The continuation at higher energies of the ACE measurements of the isotopes and rare components does not require a huge experiment. A LISA-like device, with a total acceptance < 1 m^2sr, would be enough. However the necessity of a good determination of the mass and charge of the incoming nucleus make the instrument somewhat complex. The basic scheme can consist of a magnetic spectrometer, characterized by a several kgauss magnetic field on a volume of several hundreds cm^2, for measuring the rigidity of the nucleus, complemented by detectors measuring the nucleus velocity. A magnetic superconducting spectrometer, equipped with very thin silicon strip or pixel sensors must be transported to the Moon base, but there it can enjoy of a very low coolant consumption due to the local thermodynamic conditions, and can be charged (and re-charged in case of quenching of the coils) by the locally installed power supplies. Local power supplies could be used also for the detectors, so that for running the experiment only buffer batteries should be provided from the Earth.

C. Energy spectra of antiparticles and hunting for antinuclei.

This same scheme, or perhaps the same physical apparatus itself complemented by suitable devices for identifying the electromagnetic CR component, could be used for measuring the rare elementary antiparticles (positrons, antiprotons) and hunting for antinuclei. In the next few years PAMELA, and hopefully AMS, will determine the positron and antiproton spectra up to several hundreds GeV. To push the spectra measurements up to the TeV region the acceptance and intensity of the magnetic field must be much higher than that in the case of the isotopes identification and measurement of other rare components. The magnetic field intensity must be of the 'tesla' class in a volume of a few cubic meters. These parameters can already nowadays be reached with a limited amount of mass of the coils[1].

For the measurement of the positron and antiproton spectra an interesting possibility is offered by the use of the powerful bending power of the terrestrial magnetic field. In order to use it as magnet of the spectrometer the scheme of the apparatus should foresee a precise determination of the direction of the incoming particle on an area of several m^2, in front of a tracking calorimeter where the particle could be identified and its energy measured (fig.2).

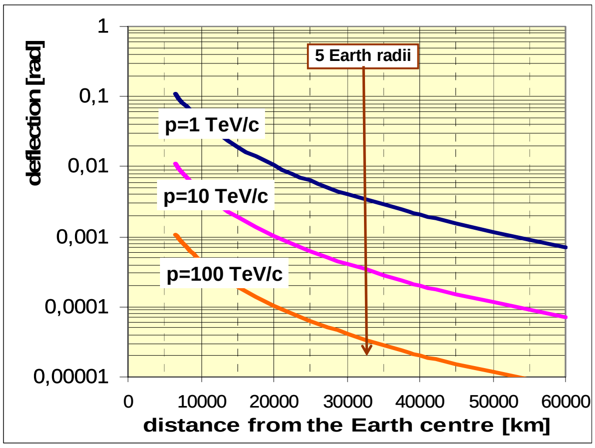

Fig. 2 – Deflection of a CR passing at different distances from the Earth magnetic axis.

The reachable energy is determined, besides the physics dominating the antiparticle flux[2], by the area and precision of the direction detector. With 100 m^2 and 1 mrad angular resolution the antiproton spectrum can be measured up to 10 TeV in case that it is dominated by the existence of primary antiprotons, as it should be for a baryon-antibaryon symmetric Universe. The maximum energies reachable for proton-antiproton steady sources and for secondary production would be much less (see again footnote 2). The mass of a system of direction measurement covering 100 m^2 could be several tons, its final minimum mass strongly depending by the technical detail of the project. In fact for a system composed by 10 layers of 200 micron thick silicon detectors the mass of the sensors would only be 4.6 kg/m^2, less than half tons for the whole 100 m^2 to be covered, negligible in comparison to all the other mechanical parameters. For the minimization of their mass it should be made recourse to inflatable mechanical systems, either for single module as well for the whole assembly.

More difficult it seems to conceive a suitable calorimeter for a first generation experiment. For its passive part it should relay on materials available on the Moon.

The solid lunar regolith could be processed and compacted in constructive bricks (they will be surely made available for other lunar programs, such as shelters for men and instruments, supports for structures and devices etc.). Already twenty years ago John Linsley, in his contribution to the NASA workshop "Future Astronomical Observations on the Moon" [28] suggested equipping by light inflatable gas detectors the thick roof of lunar shelters. For constructing the absorbing layers of the calorimeter it will be necessary a supporting structure, requiring in any case, also taking in account the low gravity pull, a large mass of structures imported from the Earth.

More promising is the use of the water that several data indicate to be abundantly present in the material of the eternally in shadow bottom of several polar craters [29]. It must be anyway underlined that a large quantity of water will be in any case required for the permanent presence of humans on the Moon [30]. A water pool could be equipped by light sensors for detecting the Cherenkov light produced by the particle and registering its pattern, e.g. in a Kamiokande-like arrangement (fig.3).

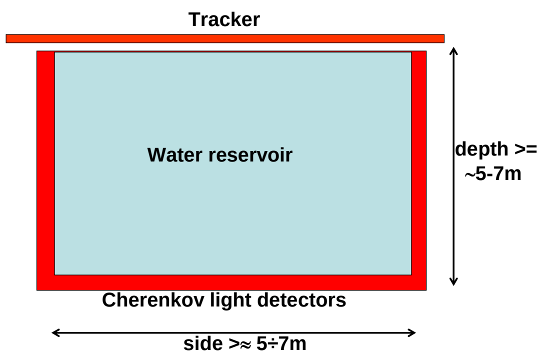

Fig. 2 – Scheme of a Kamiokande-like water calorimeter.

[1] See for example the large superconducting coil project [27] of the study of the ESA Topical Team for protecting astronauts from ionizing radiation in future interplanetary missions.

[2] In the TeV energy region the antiproton flux due to abundant proton-antiproton production from steady sources can exceed by two order of magnitude the secondary production flux, while the flux of abundant primary antiprotons at cosmological level can exceed it by four order of magnitude

Only the light sensors should be brought from the Earth, already arranged in equipped modules to be immersed in the pool. The depth of the pool must be several meters (>5) to guarantee the containment of the maximum of the shower up to a few tens TeV. For covering the above hypothesized surface of 100 m^2 a total 500 t of water would be required. According to the plant currently studied [29] in the framework of the 'MoonBase initiative' program, such a quantity of water can be collected in about 2 year by microwave heating the regolith on the permanently shadowed bottom of near-poles craters by employing 120 kw. In this scenario a spectrometer based on the bending power of the terrestrial magnetic field could be foreseen as a first generation experiment on the Moon base. It could be conceived modular, beginning to cover only a few m^2 perpendicularly to the Moon-Earth direction, growing up to a few tens or hundreds m^2, and, if advisable, distributed in different point of the base.

Much more difficult (even though not impossible) it is to push the limit for hunting antinuclei beyond the value and the energy promised by AMS-2 [7], i.e. to 10^{-7}-10^{-8} on the antihelium/helium ratio at energies approaching the TeV/particle. The values of the required acceptance should substantially scale up, and so should scale up the dimensions and mass of all the detectors around, that for this search are required to be very selective and precise. The hunting for antinuclei could be the object of a 'second generation' experiment.

D. CR Composition at the knee

The above envisaged calorimeter could also be the main device of an apparatus for measuring the elemental composition of cosmic rays at the knee, a long standing fundamental problematic of the CR physics.

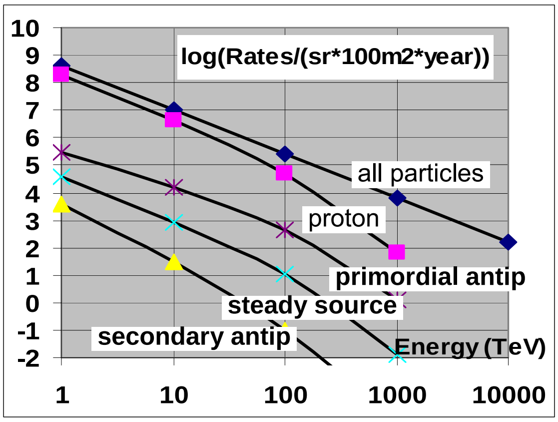

Fig. 4 – Primary CR rates as a function of the energy. Antiproton rates are also reported for the three main possible trends (from the top): baryon-antibaryon symmetric Universe; proton-antiproton pair production by abundant steady sources; proton-antiproton pair production only by interaction of primary CR on interstellar matter

The rates for a unity of 100 m^2sr of acceptance (fig.4) allow the direct measurement of the CR composition beyond 10 PeV. If realized by a water pool the calorimeter should 7x7 m^2, 5-7 m deep, what implies an amount of about 300 t of water to be produced on the Moon. According to the above mentioned study [29] such an amount of water can be produced in 1.5 years by employing 120 kw of electric power. For the measurement of the CR composition the calorimeter must be complemented with a direction and charge measurement of the incoming particle on the top. In this part inflatable bags could be added to serve as radiator for gas cherenkov detectors. This could be a basic module to be duplicated (fig.5) for increasing the maximum reachable energy by increasing the collection rate in a second phase of the experiment.

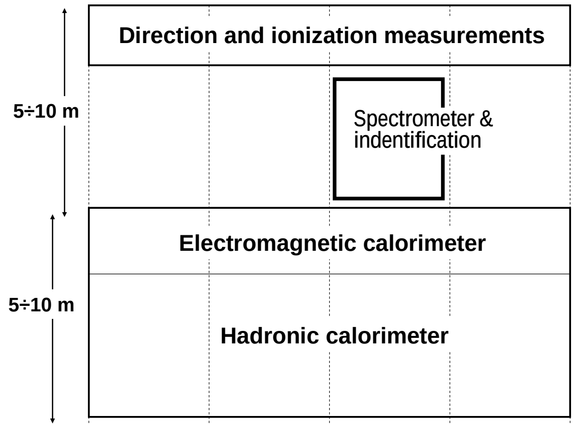

Fig. 5 – A modular system for the measurement of the CR composition. One of the modules could be specialized for rare components measurement.

The dimensions of the calorimeter are similar to those of the calorimeter of the system outlined in the above section III-*C* for the measurement of positron and antiprotons spectra, either if it will use the bending power of the terrestrial magnetic field or an independent magnet. It is possible that the two systems could be integrated in one facility to be used for both experiments.

It is worthwhile to observe that this facility, suitably equipped, could also be fitted for extending the high energy gamma ray astronomy well beyond the limits that will be reached by the GLAST experiment in next future.

A possibility, complementary or alternative to the calorimetry, is that of committing the energy and charge measurements to a telescope of Transition Radiation Detectors (TRD's) and gas cherenkov counters. A suitable choice of the parameters of a set of TRD's allows to identify the nucleus and measure its energy on a wide range, from 1,000 up to more than 100,000 of the gamma kinematical parameter, i.e. from 1 TeV to more than 100 TeV for the proton and 50 TeV to more than 5 PeV for the iron. In this range a system of 4 m diameter guarantees a useful rate. It matches the 5 m diameter of the spacecraft in preparation for the transportation to Moon, still leaving room around to an inflatable doughnut for stretching the many sheets of radiator and sensors. A TRD an cherenkov counter spectrometer could be also envisaged for the identification of the particle and the determination of its energy for the measurement of the energy spectra of the high energy rare components (isotopes, rare radioactive nuclei, antiparticles), and also in this case the measurements of the CR composition at knee and of the rare CR components could be integrated in a unique facility.

E. Ultra high energy CR's.

At energy of the primary CR exceeding 10^{17}-10^{18} eV the fluoresce emission of the shower in the terrestrial atmosphere becomes enough intense to be detectable by suitable devices. This fact allows to measure the total energy released by the CR in the shower and also to follow its longitudinal development, giving a further hint for identifying the primary CR, and possibly identifying the different CR components.

At energies enough high, exciding a few EeV, the fluorescence light emission is enough intense that can be observed and measured by one or a few devices on board of LEO satellites, opening the possibility of monitoring from far away a huge air volume of the terrestrial atmosphere. However the limitations in mass and dimensions of the transport to orbit systems will not allow in a foreseeable future to go very far in the CR explored energy and most of the region beyond the GZK cut-off will be out of reach.

The observation of the fluorescence light from a very high altitude satellite, as the Moon is, could increase by two order of magnitude the observable atmospheric volume, but, due to the three orders of magnitude of major distance from the terrestrial surface respect to the altitude of a LEO satellite, it requires a huge acceptance of the optical system for maintain a not too high energy threshold for the detection (see fig.7 in [25]). The needed diameters of the optical systems (several hundreds meter) cannot be a goal for the first generation Moon borne experiments. Diameters in this range should be taken into consideration if in the meantime the neutrinos become the fundamental actor in the astronomy of the extreme space and time Universe and of the extreme energy astrophysics, claiming for the need of an 'ultra high energy (UHE) neutrino observatory'. It must be in fact observed that, beside the 'less improbable' cosmogenic neutrinos[3], several models foresee significant neutrino fluxes at 10^{22} eV and beyond. The results of the UHE CR experiments performed in the meantime will say of their importance and will drive the parameters of the possible Moon based UHE neutrino observatory.

An interesting perspective for the observation of UHE CR's is offered by the LORD projects [31]. The basic idea is the detection by a lunar satellite of the 'Cherenkov light' emitted (in the radio frequencies) by the shower produced by the UHE CR on the limb of the Moon. The monitored target volume increases with energy and becomes competitive for energies beyond 10^{20} eV (fig. 6, adapted from [25]).

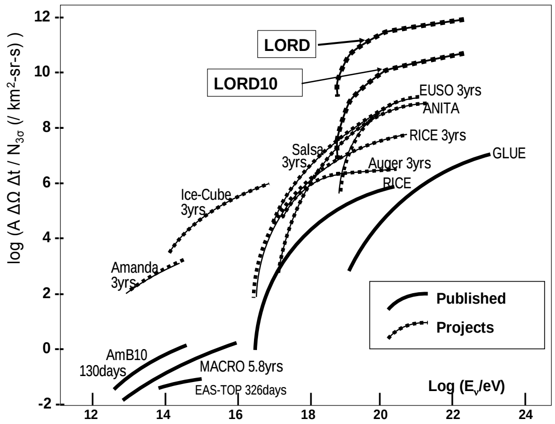

Fig. 6 – Observable target volume for different experiment. LORD and LORD100 projects are based on the detection of the radio signal emitted by the Ultra HE shower produced by primary CR on the limb of the Moon.

Such a device, also if not installed on the Moon surface, could usefully profit of the facilities of a future Moon base, and considered a Moon based experiment. In order to base on this technique an UHE neutrino observatory it will be critical to understand how to extract the effect due to neutrino originated showers from the much more abundant number of showers originated by charged nuclei.

IV. Conclusions

There are several important measurements that can be conducted on the Moon surface already at the very beginning of operation of the Moon Base, by using apparatuses based on techniques nowadays available. The *combination of all these measurements in a single base* represents a very challenging and really advanced program, both because of the advantage of using common facilities and because of the possible synergy of different detection systems and measurements.

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