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# High-altitude stations and high energy cosmic rays(*)

L. W. Jones
*Department of Physics, University of Michigan - Ann Arbor, USA*

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**Summary.** — The advantages of high-altitude ground-based cosmic ray stations have been discussed in many past reports and conferences. It is very satisfying to observe this renewed attention to the research potentials of the Chacaltaya Laboratory. Specific research opportunities are reviewed, and possible future scenarios are noted.

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## 1. – Introduction

Before opening this discussion of Chacaltaya and of the research potentials of high altitude laboratories, I should like to bring to this Conference the greetings of two of my University of Michigan colleagues, Wayne Hazen and Fred Hendel. Fred was cited in the opening session of this meeting for his role in engineering the road to Chacaltaya in the early years of the laboratory. Later, he and Wayne studied the radio frequency pulses generated by extensive air showers in research at Chacaltaya.

It was my priviledge to attend two previous conferences in La Paz, and to visit the Chacaltaya Laboratory on both of those occasions: in 1970 and in 1982. I was stimulated, even before the 1982 meeting, to argue the case for the exploitation of ever higher-altitude research stations, beginning with a short note in CosNews [1], and followed by discussions at the Paris International Cosmic Ray Conference [2]. At the 1982 meeting in Rio de Janeiro (following the LaPaz meeting), I noted the potential advantages of developing a Latin American organization analogous to CERN to promote and coordinate research at Chacaltaya [3]. I was very pleased to learn of the action of the Centro Latinoamericano di Fisica in support of the Chacaltaya Laboratory from Professor Saavedra and, in his talk to the opening session of our meeting, from Professor Masperi; this is essentially what I was discussing 18 years ago. At subsequent meetings, I have again discussed

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the desirability of research stations at even higher altitudes, for example in Tibet at elevations above 6000 or even 6500 meters [4-7]. In fact, to date there is no rush to develop such laboratories, and (as I had pointed out in those discussions) the Chacaltaya Laboratory has been, regrettably, under-utilized.

## 2. – Physics issues

Of course, the motivation for cosmic ray studies at high-altitude, ground-based stations is the desire to reduce the atmospheric overburden while retaining the ability to deploy detector systems both larger in area and more massive than can be carried in balloons or satellites. At Chacaltaya, the overburden of 540 g/cm$^2$ is about 7 nuclear interaction mean free paths, so that the primary cosmic ray proton flux will be reduced by a factor of about 1000 at this elevation. Actually, this is somewhat pessimistic, as a fraction of the proton cross-section is diffraction inelastic. Protons which interact diffractively continue with virtually their full energy, and the diffraction products from the target nucleus fly off at such large angles and (relatively) low energies that they are not a factor in ground observations. Protons from more inelastic interactions also continue, at reduced energy, but are still sufficiently abundant to provide interesting interactions for emulsion chamber studies. Heavier primary nuclei are generally diffractively dissociated into their constituent nucleons high in the atmosphere, so that the mountain-top observations of direct high energy interactions are limited to nucleons.

In earlier talks [2, 5], I had noted three motivating issues for high-altitude cosmic ray studies. They were: A) the study of primary composition aroung the "knee" of the primary spectrum (1–10 PeV), B) the study of features of the primary interaction, such as scaling, inelasticity, $K_\gamma$, and C) further study of exotic phenomena, such as Centauros, Chirons, the Long-Flying Component, etc. Remarkably, over the past two decades, these same areas still remain! With regard to A) and B), it has been noted repeatedly that a broad diversity of cosmic ray experiments is required, with measurements of air showers together with muons (energy and angular distributions), hadrons (also with energy and angular dependences), and at different elevations in order to find the model of the primary interaction and the primary composition which best match all the data [8]. The problem, of course, is that the observable consequences of primary composition and the character of the first interaction are closely interrelated, and no simple observations are able to unambiguously fix the composition independent of the physics of the first interaction, and vice versa. In this context, data from Chacaltaya, of the character and detail of the data being produced by the KASCADE Collaboration at Karlsruhe, would be extremely valuable.

With regard to exotic phenomena, the mysteries of these observations have been with us for decades, and in spite of models and some accelerator experiments, they remain mysteries [9]. Surely further, more refined (if possible) observations from as high an elevation as possible are called for. Although some of the observations of exotic phenomena come from balloon-borne detectors, such as the JACEE emulsion chambers, most are from Chacaltaya, the Pamirs, and other mountain top emulsion chamber exposures.

## 3. – Future directions

In planning this discussion before the Conference, I drew up a short list of research areas which would profit from a high-altitude location. I was delighted to learn that, in fact, many of these areas will be studied at Mt. Chacaltaya. For example, the BASJE array continues to study the character of primary interactions in the vicinity of the knee, and emulsion exposures continue the searches for and studies of exotic phenomena. I also welcome the results of the studies of event "families" (with emulsion chambers) with their accompanying air showers.

High energy gamma-ray astronomy can also profit from high-elevation observations, to fill in what had been a gap between the air shower observations, historically sensitive to energies of 100 TeV and above, and the air Cherenkov optical telescopes, such as Whipple, which are mostly sensitive to energies below 0.3 TeV. The lower energy limit on air shower studies is set by the thickness of the atmosphere in radiation lengths; the depth to which an air shower penetrates is proportional to the primary gamma-ray energy. The air shower threshold has been pushed to below 10 TeV with arrays such as the Yang Ba Jing array in Tibet (at over 4000 m), and will be brought even lower with the ARGO (continuous coverage resistive plate chamber) array being built there. From the many presentations at this conference on the subject of gamma-ray astronomy, it is clear that the potential of Chacaltaya will be exploited in this area.

Because the atmospheric water vapor absorbs infra-red and microwave radiation, and the water vapor content of the atmosphere fall more rapidly with elevation than the barametric pressure, high-altitude sites are particularly desireable for infrared and microwave astronomy. I was glad to note the astronomical dome now on Mt. Chacaltaya, and to learn of the plans of the Boomerang collaboration (which has been in the news recently with their high-resolution studies of the 2.7 K microwave background radiation) to set up observations at Chacaltaya.

During the 1960s, when my group was undertaking cosmic ray studies on Mt. Evans in Colorado (4300 m), we interacted with a medical group studying the physiological effects of high altitude on a group of subjects; the subjects and researchers were, in fact, also from the University of Michigan. This interaction showed me that there was interesting potential research in other areas of science besides cosmic ray physics and astronomy at high altitudes. And for this reason I was delighted to learn of the Danish studies of physiological adaptation carried out at the Chacaltaya Laboratory.

Hence, essentially all of the areas I had planned to discuss in this presentation are being addressed, much to my pleasure.

## 4. – Desiderata

I believe that we have all been very impressed by the research program with the KASCADE detector array at Karlsruhe, where a dense air shower array, incorporating muon detection in each air shower station, surrounds a large central array of hadronic calorimetry and energetic muon detection. The results of these studies and of the sophisticated Monte Carlo studies carried out by the Karlsruhe group have led to significant advances in our understanding.

It seems to me that an ideal project for Chacaltaya would be a 5200 m analogue of this detector array. Data similar to that collected at Karlsruhe (at essentially sea level) from the Chacaltaya elevation would be very valuable in further resolving the problems of the cosmic ray knee discussed above. There may be at least two differences in a Chacaltaya array as compared with KASCADE. First, the hadron calorimeter should, ideally, contain a high-resolution detector system in its upper layers (silicon strips?) in order to resolve separate hadrons in and near the event cores. It should also have an area of about 100 m$^2$, to adequately sample the cores of 10 PeV showers (where the rate is only 1 per m$^2$-year). I cannot appraise the practicality of developing a large-area electronic analogue to the emulsion chamber. Silicon may be too expensive. Scintillator strips or high-resolution RPCs may be more realistic. If such detectors are not practical, one could revert to emulsion chambers.

Second, as some showers may reach the detector level close to or even above shower maximum, the shower detectors should ideally be of two layers, separated by an absorber of perhaps a thickness of one radiation length. Above shower maximum, the lower detector would show a greater pulse height (particle count) than the upper one, due to cascading and conversion in the absorber. Below shower maximum, the lower detector would show a smaller pulse height than the upper one, due to absorption of the lower energy electrons and gammas. Whether the absorber should be lead, or perhaps some lighter material with a critical energy close to that of air would have to be decided based on Monte Carlo studies. As at Karlsruhe, a third scintillator should be added, below a suitable absorber, to detect low-energy muons at each station as well.

## 5. – Neutrons

In the past I have noted the possibility of detecting showers initiated by primary neutrons. The point is that a proton, accelerated in a supernova shock (or similar stellar environment) would have a reasonable probability of interacting with material in the accompanying plasma. These same interactions would probably also generate neutral pions, hence high-energy gammas. However the average energy of the gammas would be a couple of orders of magnitude below that of the initiating proton (or heavier nucleus). From experiments at the Fermilab synchrotron, we know that, from inelastic collisions with nuclei, about a fourth of the final state, high-energy nucleons are neutrons, with a nearly flat energy spectrum (up to the energy of the incident proton). Hence the average energy of the produced neutrons would be much closer to that of the initiating proton than that of the gammas. And diffraction dissociation of heavier accelerated nuclei would produce neutrons and protons of the same energies. Of course the 886 s decay mean life of a neutron limits the range from which they might reach the Earth. However for nearby sources within our own galaxy, we should be sensitive to possible point sources. The decay mean free path for a 1 PeV neutron is about 10 parsecs, and of a 10 PeV neutron, 100 pc.

## 6. – Comments

In the references cited above, I have pressed the case for a “really high altitude” cosmic ray station, probably in Tibet. I still believe that this is an appropriate future project for our scientific community, but I admit that it will not be undertaken soon. In the meantime, the Chacaltaya Laboratory is here, functioning, capably administered, and welcoming new initiatives. Surely our community should exploit its potentials and support the research activities located at this Laboratory.

Cosmic ray physics has been the motivating science behind mankind’s pioneering venture into frontier environments over the past half century. It was the study of cosmic rays which led Van Allen to the early exoatmospheric rocket studies, and Grigorov to the pioneering Proton satellite program. The Antactic South Pole Station is home to the AMANDA and SPASE detectors. When mankind establishes a station for continuous habitation at an elevation requiring an oxygen-enriched environment, you can be certain that the objective will be cosmic ray research!

TABLE I. – *High-altitude cosmic ray research stations.*

| Station name | Host country | Elevation | Atmospheric pressure |
|---|---|---|---|
| Kamba La | Tibet | 5450 m | 520 $g/cm^2$ |
| Mt. Chacaltaya(*) | Bolivia | 5220 m | 540 $g/cm^2$ |
| Pamirs | Tadjikistan | 4380 m | 596 $g/cm^2$ |
| Yang ba Jing(*) | Tibet | 4300 m | 606 $g/cm^2$ |
| South Pole(*) | Antarctica | 2835 m | 650 $g/cm^2$ |
| Mt. Fuji(*) | Japan | 3776 m | 650 $g/cm^2$ |
| Tien Shan(*) | Kyrgyzstan | 3250 m | 680 $g/cm^2$ |
| Mt. Aragatz(*) | Armenia | 3200 m | 690 $g/cm^2$ |
| Mt. Norikura(*) | Japan | 2700 m | 740 $g/cm^2$ |
| Ootacamund(*) | India | 2200 m | 800 $g/cm^2$ |
| La Palma(*) | Canary Islands | 2200 m | 800 $g/cm^2$ |
| Gran Sasso(*) | Italy | 2005 m | 810 $g/cm^2$ |

(*) Electric power on site.

Table I, included in the Utah Cosmic Ray Conference paper [7], is a useful reference to the global cosmic ray research domain.

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