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MEMORANDUM

To: J.B. Dainton, SPSC Chairman, CERN

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cc: M. Budel, J. Engelen, H. Taureg

Date: August 13, 2004

Subject: **CERN Proposal SPSC/P317; the CLOUD experiment**

Summary: The CLOUD collaboration [1] submitted a proposal to CERN in 2000 to investigate the microphysical interactions of cosmic rays and clouds [2]. However, in view of the emerging budget difficulties for the LHC, a decision on the experiment was postponed until the LHC resources had been clarified. It is the purpose of this memorandum to re-state the strong interest of our collaboration to carry out this experiment and briefly to review the scientific and technical developments since the original proposal. The CLOUD collaboration requests conditional approval of the experiment by CERN to allow us to apply for experimental funding from national and EU agencies. Once the necessary funds are obtained, we would request full approval and the establishment of a Memorandum of Understanding between CERN and the collaborating institutes for the construction and operation of the experiment.

1 OVERVIEW

The CLOUD experiment is motivated by numerous indirect observations and theoretical studies that suggest galactic cosmic rays (GCRs) may exert a significant influence on clouds and climate. Increased GCR intensity is associated with cooler temperatures and, as suggested by satellite observations, with increased cloud cover at low altitudes [3]. However since the physical mechanism is experimentally unknown, the possible influence of cosmic rays on clouds remains an open question. It is, nevertheless, important to resolve this question since clouds exert a strong control over Earth's radiative energy balance. The observed variation of low clouds by about 1.7% absolute over one solar cycle corresponds to a change in Earth's radiation budget of about 1.2 Wm^{-2}. This change in energy input to the lower atmosphere is highly significant when compared, for example, with the estimated radiative imbalance of +1.4 Wm^{-2} from anthropogenic CO_2 emissions since the Industrial Revolution. Moreover, the mean GCR intensity declined by about 15% during the 20^{th} century due to a doubling of the solar wind (open solar magnetic flux) [4]. This net reduction of GCR intensity is about the same magnitude as the change

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Fig. 1: Sources of variation of the galactic cosmic ray intensity on Earth. The GCR intensity is decreased by a) increased solar wind (on typical timescales of 10–1000 yr), b) increased geomagnetic field (1–100 kyr), and c) passage of the solar system out of a spiral arm of the Milky Way (>10 Myr).

observed over one solar cycle. If clouds are indeed influenced by cosmic rays then these long-term changes of GCR intensity could contribute to temperature changes over the last 100 years, effectively amplifying the solar contribution with a new *solar indirect* effect. In order to accurately represent the solar contribution in climate models, it is vital to understand the cause of the cloud variations and the significance of this possible solar indirect component.

The aim of CLOUD is to investigate and quantify cosmic ray-cloud mechanisms under controlled laboratory conditions using a CERN particle beam as an artificial source of cosmic rays that simulates natural conditions as closely as possible. The concept of CLOUD is to build a general purpose detector with sufficient sensitivity and flexibility to explore this relatively unknown field. The apparatus includes an advanced cloud chamber and reactor chamber where the atmosphere is realistically represented by moist air charged with aerosol and trace gases. The chambers are equipped with a wide range of external instrumentation to monitor and analyze their contents. The thermodynamic conditions anywhere in the troposphere and stratosphere can be re-created within the chambers. In contrast with experiments in the atmosphere, CLOUD can compare processes when the cosmic ray beam is present and when it is not, and all experimental parameters can be controlled.

The experimental programme will include the effects of cosmic rays on the creation and growth of aerosols in the presence of trace condensable vapours, the activation of aerosols into cloud droplets, the formation of trace molecules such as NO and OH and their effect on cloud processes, and the creation and dynamics of ice nuclei [2, 5]. Each topic will involve several experiments, each one focusing on a particular trace vapour or mixture of vapours. A single experiment requires about 4 weeks beam time. We request 8 weeks beam time for checkout plus 48 weeks for data taking (corresponding to 12 experiments), spread over a 3 year period. The apparatus would be ready for the first beam about 2 years after approval and funding, implying first operation would be possible in 2007.

Since the physical processes to be studied by CLOUD are highly non-linear, it is important to re-create experimental conditions that are as close as possible to those occurring naturally. This implies that the π/μ beam should be near minimum ionizing, and have a time-averaged intensity corresponding to cosmic rays at the altitude under study. The beam must also have sufficient energy to penetrate the material of the cloud chamber and reactor chamber without large scattering or energy loss. The latter requirement implies a *minimum* π/μ momentum of about 1 GeV/c. CERN is the only European accelerator that can provide secondary beams at this energy or above. The beam must be spread over an area of 200×200 cm^2 in order to uniformly irradiate the cloud chamber and reactor chamber. Time-averaged beam intensities between 1 kHz and 100 kHz are required, corresponding to the GCR intensity between ground level and 20 km altitude, respectively. We request to install CLOUD in the East Hall and operate in a secondary beamline at the CERN PS. The entire experiment could be mounted on a moveable platform to allow other users access to the beamline during CLOUD downtime.

The experimental deliverables are twofold. Firstly, CLOUD will provide a quantitative understanding of the effects of cosmic rays on aerosols and cloud droplets, including ice formation. Secondly, we will use the laboratory results to incorporate cosmic ray mechanisms into aerosol and cloud models. These models will be used to assess the importance of cosmic rays on cloud development in comparison with natural variations of other parameters in the atmosphere.

2 CLIMATIC EVIDENCE

Since the original proposal, the scientific case for the CLOUD experiment has strengthened considerably. A wide range of new instrumental and palaeoclimatic evidence has been published that indicates a link between cosmic rays and climate on all time scales. Furthermore, the first evidence has been reported for ion-induced nucleation of new aerosol in the atmosphere, supporting the expectations from modeling studies. The climatic evidence, on progressively longer timescales, comprises:

1. The correlation between GCR intensity and Earth's average low cloud cover and during one solar cycle [3] has been extended in time to cover 1983–2001. These correlations, based on data from satellites and neutron monitors, have been subjected to intense scrutiny and criticism [6]. The new data suggest a solar/GCR modulation of low clouds superimposed on a decreasing trend[1] [7]. Although the most recent satellite data are not yet available, an independent study of Earth's albedo had been made from 'Earthshine' on the shadowed part of the Moon [8]. A rising reflectivity (cloudiness) of Earth over the period 2001–2003 is observed, correlating with the increasing GCR intensity over this phase of the solar cycle.

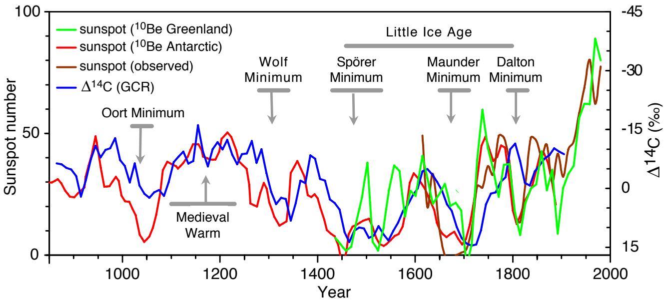

Fig. 2: Variation of GCR intensity (blue curve) and mean sunspot number (red, green and brown curves) over the past millenium [9]. The sunspot number is reconstructed from the GCR intensity recorded in the ^{10}Be concentrations of ice cores from Greenland and Antarctica. Recorded periods of cool (minima) and warm climates are indicated by grey bars. The time lag of ^{14}C with respect to ^{10}Be is due to the long residency time of ^{14}C in the atmosphere.

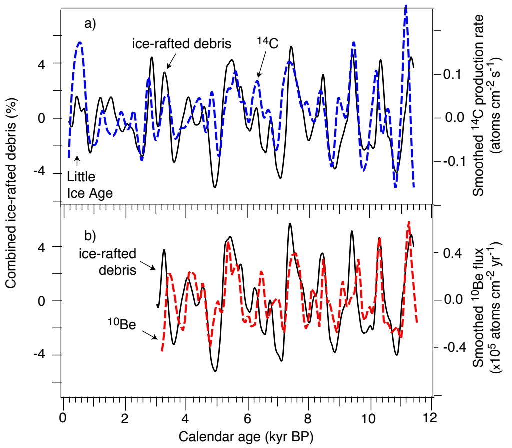

Fig. 3: Correlation of GCR variability with ice-rafted-debris cold events in the North Atlantic during the Holocene [10]. The GCR records are based on a) ^{14}C and b) ^{10}Be.

2. The GCR intensity has varied considerably in the past on 100–1000 year timescales, and persuasive evidence for a significant solar/GCR influence on climate has emerged from new palaeoclimatic

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[1] This apparent decreasing trend may be an instrumental effect since a possible discontinuity of the satellite calibrations around 1995 has been reported [7], coinciding with a 6-month gap of the polar-orbiting satellite normally used to inter-calibrate the geostationary satellites.

studies. The association of GCR intensity with documented warm and cold periods over the last millenium is well established (e.g. Fig. 2 [9]). The Little Ice Age around the 17^{th} century coincided with an almost complete absence of sunspots, and an elevated GCR flux around 25% higher than today. Rather than an isolated ocurrence, this appears to be merely the most recent of around 10 such cold events during the Holocene when North Atlantic Ocean surface temperatures fell by around 2°C, coincident with periods of high GCR flux (Fig. 3 [10]). Another recent observation of a strong correlation between cosmic rays and climate is shown in Fig. 4 [11]. The data show that monsoon rains in Oman (δ^{18}O in a U-Th-dated stalagmite from Hoti cave, Oman) over the period 6.2–9.6 kyr BP were controlled by solar/GCR variability. Water availability in this region requires a warm climate and monsoon rains brought by a northward shift of the Inter Tropical Convergence Zone (ITCZ) in summer.

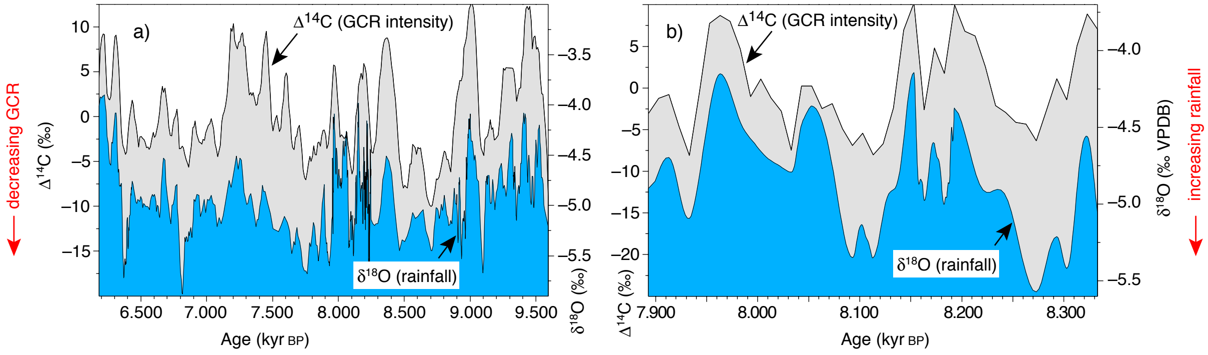

Fig. 4: Profiles of monsoon rainfall (δ^{18}O) recorded in a U-Th-dated stalagmite from a cave in Oman, together with GCR intensity (Δ^{14}C) recorded in tree rings in California, for a) the 3.4 kyr period from 9,600 to 6,200 yr BP (before present) and b) the 430 yr period from 8,330 to 7,900 yr BP [11].

3. On 100 yr timescales, variations of the cosmic ray flux are generally thought to reflect changing solar activity (increased solar magnetic activity reduces the GCR flux). This results in the ambiguity of whether cosmic rays exert a direct effect on Earth's climate, or else serve as a proxy for long-term variability of the solar irradiance (which would be of considerable scientific importance in itself). However, recent high-resolution palaeomagnetic studies suggest that short-term geomagnetic variability may in fact control a significant fraction of the GCR modulation within the Holocene, even on 100 yr timescales [12]. Since the geomagnetic field modulates only the GCR flux and not solar radiation, this suggests a direct effect of cosmic rays on the climate. This is supported by recent satellite observations that the amplitude of the GCR-cloud effect increases at high latitudes [13]. Furthermore, evidence has recently been presented that climate changes over the last two glacial cycles appear to be linked to geomagnetically-induced variations of the cosmic ray flux. It is proposed that the ice ages may initially be driven not by insolation cycles, as in the standard Milankovitch model, but by cosmic ray changes [14]. This conclusion is drawn from a wide range of evidence, including the periodic growth of speleothems in caves in Austria and Oman, and the record of cosmic ray flux over the past 220 kyr obtained from the ^{10}Be composition of deep-ocean sediments.

4. On much longer timescales, up to 1 Gyr, evidence has been reported for the occurrence of ice-age epochs on Earth during crossings of the solar system with the galactic spiral-arms [15], when elevated GCR fluxes are expected due to the higher production rate and diffusional trapping of charged particles by the interstellar magnetic fields. A correlation is observed between the reconstructed GCR fluxes and ocean temperatures during the Phanerozoic (past 550 Myr), with an aproximate periodicity of 140 Myr.

3 MECHANISMS

The instrumental and palaeoclimatic data suggest that Earth's climate may be sensitive to surprisingly small changes of GCR intensity of around 10%. Several mechanisms have been proposed by which GCRs could affect clouds [16, 17], although none is experimentally established. The most promising candidates are:

1. Ion-induced nucleation of new aerosol: Modelling studies [18, 19] and atmospheric observations [20, 21] by members of our collaboration and others indicate that cosmic rays may enhance the nucleation and early growth of ultrafine condensation nuclei from trace precursor vapours such as H_2SO_4 in certain regions of the atmosphere (Fig. 5). These may eventually grow and increase the CCN (cloud condensation nuclei) number concentration, which would increase cloud lifetimes and reflectivity, thereby influencing the global radiative energy balance. Depending on the location, new particle production can more than double the CCN number concentration over the course of a day. Atmospheric new-particle production is therefore an essential process that must be understood and incorporated into regional and global climate models.

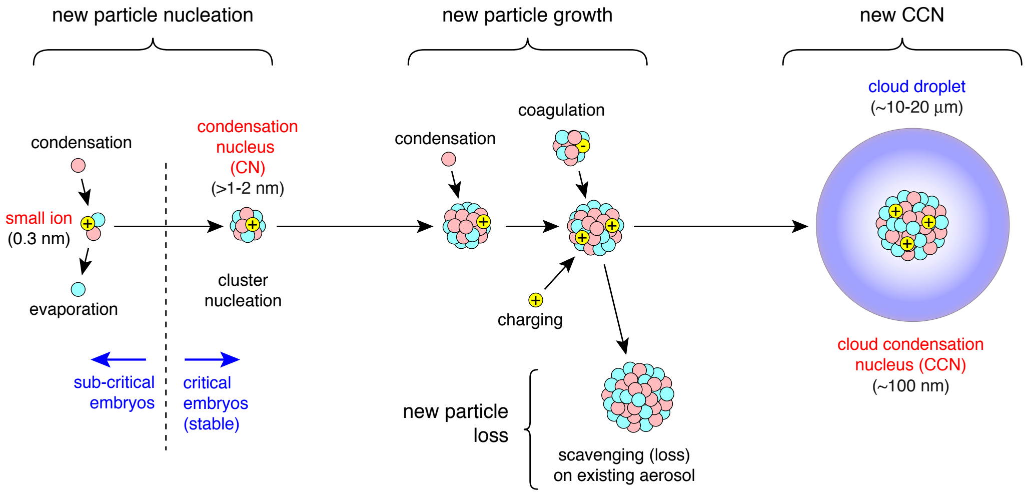

Fig. 5: Ion-induced nucleation of new particles from trace condensable vapours and water in the atmosphere. The presence of charge stabilizes the embryonic cluster and reduces the critical size for continued growth rather than evaporation. Charge also accelerates the initial rate of growth of the cluster due to enhanced vapour condensation. In consequence, limited by the available charge from GCRs, new particles can form even in the presence of exceptionally low concentrations of trace vapours, as occurs in widespread regions of the atmosphere. Provided there are few existing aerosol (clean environment), some of these new particles may grow sufficiently to become new cloud condensation nuclei which seed cloud droplets.

2. Ice particle formation: Field measurements show that clouds contain a great deal of supercooled liquid water in the temperature range 0°C to -40°C, since nuclei that induce ice formation (*ice nuclei*) are rare in the atmosphere. Enhanced heterogeneous ice nucleation by electrification has been proposed [22]. The vertical conduction current from GCR ionisation generates highly charged droplets ($\gtrsim$100 e) at the upper and lower boundaries of clouds. When these droplets evaporate they leave behind highly charged and coated "evaporation nuclei" which may constitute efficient ice nuclei. The presence of charge enhances collisions of the evaporation nuclei with other liquid droplets by "electroscavenging", thereby generating ice particles in clouds. This would imply that increased GCR intensity leads to increased ice particle formation in clouds. The associated rainfall and release of latent heat might influence atmospheric dynamics, for which there is some evidence [22, 23].

4 CLOUD EXPERIMENT

The key to further progress on the cosmic ray-cloud-climate question is to understand the physical mechanism. This requires an experimental study of the fundamental microphysical interactions between cosmic rays and clouds. Demonstrating overall cause and effect in the atmosphere beginning with changes in ionisation rate and ending with observations of perturbed clouds will be quite challenging. For this reason CLOUD proposes to study GCR-cloud microphysics under carefully controlled conditions in the laboratory using a CERN π/μ beam as an artificial source of cosmic rays.

The beam passes through a 2 m diameter reactor chamber and a 0.5 m expansion cloud chamber in which dynamical conditions within clouds throughout the troposphere or stratosphere can be reproduced (Fig. 6). An advanced control system will allow precise dynamical positioning of the piston displacement to simulate rising air parcels and activation/evaporation cycles in clouds, and to compensate for wall heating. A field cage generates electric fields in the range 0–10 kV/m, corresponding to the electrification of fair-weather clouds.

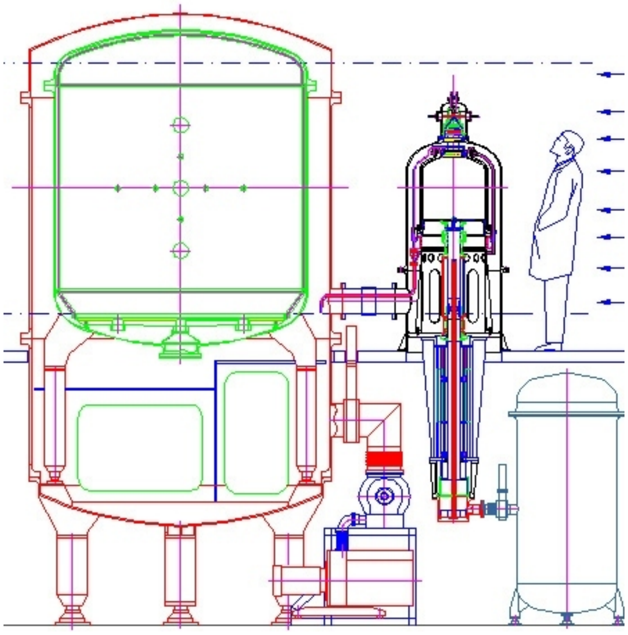

Fig. 6: The CLOUD experiment, showing the 0.5m cloud chamber and 2m reactor chamber. The transverse size of the π/μ beam is 2m.

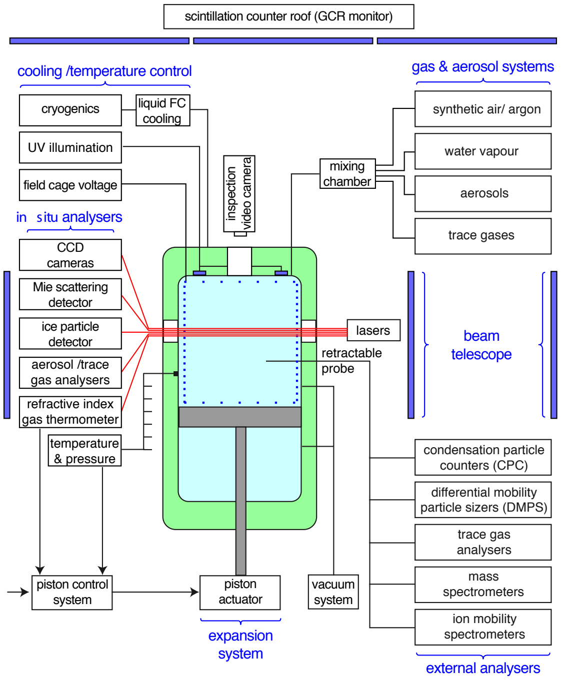

Fig. 7: Subsystems and instrumentation for CLOUD (the reactor chamber is not shown).

The cloud chamber and reactor chamber operate in the pressure range 0–1 atm and in the temperature range 185–315K, maintained by a surrounding liquid fluorocarbon bath. The expansion cloud chamber can generate water vapour supersaturations in the range 0.01–700%, corresponding to droplet activation on particles of size between about 100 nm (CCN) and 0.1 nm (small ions). The walls of the chambers and the gas supply pipes can be cleaned by vacuum bakeout between experiments (which may involve trace gas concentrations as low as parts per trillion). The chambers are equipped with a range of external instruments for analysis and control, including mass spectrometers, ion mobility spectrometers, condensation particle counters, Mie scattering detectors, CCD cameras and trace gas analyzers (Fig. 7).

5 RESOURCES

CERN contribution: Although there is no precedent for climate research at a particle accelerator, CLOUD is technically quite similar to a typical particle physics experiment, involving the design, construction and integration of an advanced general purpose detector for operation in a particle beam. Moreover the experiment will use many of the tools and techniques of particle physicists, such as an expansion cloud chamber [2], advanced slow control systems and GEANT computer simulations. CLOUD represents an unprecedented opportunity for particle physics to contribute its techniques and expertise to address a fundamental question in solar-terrestrial physics that is of potentially great importance to society.

There are essentially two requests for CERN to provide as the host laboratory and as a member of the experimental collaboration:

1. A π/μ secondary beam from the CERN PS. The T11 beamline (3 GeV/c π) in the East Hall would be suitable.
2. Technical and scientific support for the design and construction of the cloud chamber and reactor chamber, and for the integration of the experiment together with the external instrumentation.

Collaboration: The physics of CLOUD basically concerns the atmosphere and climate. However the science also embraces palaeoclimatology, geomagnetism, solar and heliospheric physics, astrophysics, cosmic ray physics and particle physics. The experiment therefore requires a fusion of techniques and expertise from a wide range of disciplines. The CLOUD collaboration brings together the required expertise. Many members of the collaboration are currently involved in related modelling studies or atmospheric observations with surface, airborne and satellite experiments, and close feedback is expected between the field results and those obtained obtained in the laboratory with CLOUD.

Cost: The cost of the main detector (i.e. cloud chamber, reactor chamber, gas/aerosol and data acquisition systems, but excluding external instrumentation such as mass spectrometers, etc.) is estimated to be 5 MCHF (materials and personnel). The collaboration would seek external funding for the main detector, as well as for the external instrumentation.

References

[1] CLOUD collaboration: *Univ. Aarhus*, Denmark; *Univ. L'Aquila*, Italy; *Univ. Bergen*, Norway; *Univ. Bucharest*, Roumania; *California Institute of Technology*, USA; *CERN*, Switzerland; *Danish Space Research Institute*, Denmark; *École Polytechnique*, France; *Finnish Meteorological Institute*, Finland; *Univ. Helsinki*, Finland; *Ioffe Physical Technical Institute*, Russia; *Univ. Kuopio*, Finland; *Lebedev Physical Institute*, Russia; *Univ. Leeds*, UK; *Univ. Mainz*, Germany; *Max-Planck Institute for Nuclear Physics - Heidelberg*, Germany; *Univ. Missouri-Rolla*, USA; *State University of New York at Albany*, USA; *Univ. Reading*, UK; *Rutherford Appleton Laboratory*, UK; *Tampere University of Technology*, Finland; and *Univ. Vienna*, Austria.

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