PUBLISHABLE SUMMARY
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CLOUD-ITN
Marie Curie Initial Training Network No. 215072

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Summary of project objectives

CLOUD-ITN established a multi-site network of early stage researchers (ESRs) and experienced researchers (ERs) at 8 partner institutions across Europe to investigate various aspects of the interactions of cosmic rays with aerosols and clouds, which bears on the possibility of a "solar indirect" contribution to climate change. The major focus of the network was on several sets of common experiments on ion-induced nucleation and ion-aerosol interaction conducted at the newly established CLOUD aerosol chamber that is exposed to a CERN elementary particle beam where the effects of cosmic rays on aerosol and cloud formation can be efficiently simulated.
A comprehensive training program was set up for ITN fellows including annual summer schools and workshops in addition to the national PhD programs of their hosting institutions.
Key scientific objectives of CLOUD-ITN included:

- *New experimental results on aerosol nucleation:* Conduct beyond-state-of-the-art experiments of atmospheric relevance for neutral and ion-induced aerosol nucleation and early aerosol growth.
- *Assessment of the impact of cosmic rays on ions, aerosols and clouds:* Quantification of the relevance of ion-induced nucleation for the atmosphere.
- *New input for global climate models:* Parameterised inclusion of ion-induced aerosol formation and growth mechanisms for global climate models.

Work performed within the project

The CLOUD aerosol chamber was designed and constructed. It is unique in the world in its combination of supply gas and surface cleanliness, temperature control and stability, as well as control of ion production providing well-controlled homogeneous experimental conditions. A suite of state-of-the-art instrumentation is used for detailed characterization of the gases, ions, clusters and aerosol particles.
In total, 12 Early Stage Researchers (331.5 researcher-months) and 2 Experienced Researchers (48 mths.) were employed.

EXPERIMENTS

Five series of aerosol nucleation experiments took place at the CLOUD aerosol chamber at CERN focusing on binary nucleation of sulfuric acid and water and on several ternary nucleation systems adding either ammonia or dimethylamine or pinanediol to the sulfuric acid-water system. More than 900 individual experiments were conducted in total.

ITN TRAINING ACTIVITIES

Three summer schools, one winter school, numerous data workshops and other trainings were conducted. All ESRs completed secondments in addition to their extensive stays at CERN. The private sector was closely involved in the training and research activities. Complementary trainings were performed.

ITN WORKSHOPS AND CONFERENCES OPEN TO EXTERNAL SCIENTISTS

A CLOUD-ITN Open Data Workshop at University of Vienna, AT, 16-18 Feb 2011, with 60 participants (25 external) and a CLOUD-ITN Open Conference at Königstein, GER, 22-25 May 2012, with 90 participants (50 external) were conducted. ITN fellows presented results to many world-leading experts.

Main scientific results achieved

- First measurement of molecular composition of nucleating aerosol particles at atmospheric conditions.
- Discovery of "acid-base-stabilisation" nucleation mechanism.
- Observation that binary nucleation cannot account for nucleation in the atmospheric boundary layer.
- Observation that ternary NH_3 nucleation cannot account for boundary layer nucleation (contradicting previous assumptions by global models).
- Discovery of large enhancement (factor 2-10) from ion-induced nucleation for these particles.
- First measurement of molecular composition of nucleating aerosol particles with amines under atmospheric conditions.
- First observation of a huge enhancement of neutral H_2SO_4 dimer formation directly linked to the presence of amines.
- First measurement of molecular composition of nucleating aerosol particles involving oxidised biogenic monoterpenes under atmospheric conditions (oxidised by exposure to sunlight).
- First observation that highly oxidised organic species from atmospheric VOCs bond with single H_2SO_4 molecules and provide an efficient nucleation pathway.
- First measurements of the contribution of ion-induced to organics ternary nucleation involving amines and VOCs.
- First detailed molecular analysis of the type of organic species involved in particle nucleation.
- Observation of markedly enhanced growth rates for initial (sub-3nm) aerosol growth.
- First global assessment of free tropospheric nucleation - including the influence of ions from galactic rays as well as influence of NH_3- that is based on controlled laboratory measurements (previous studies have relied on empirical parameterisations and theoretical estimates).

DISSEMINATION

- 18 peer-reviewed papers published.
- First CLOUD results were published in *Nature* (Kirkby et al., Nature, 476, 429-433, 2011).
- Numerous results are currently submitted or in preparation for publication (~15 papers).
- Results were presented at various international conferences (>60 contributions, various invited), e.g. invited plenary presentation at the European Aerosol Conference, Manchester, September 2011: "Atmospheric nucleation in the CERN CLOUD experiment" by J. Kirkby.
- Two websites are maintained and frequently updated.

DELIVERABLES AND MILESTONES

All deliverables and milestones of the project were successfully completed.

Final results and their potential impact and use

CLOUD proved to significantly advance our fundamental understanding of aerosol nucleation and growth mechanisms and therefore it advances our understanding of atmospheric aerosol budgets and clouds. It provides a wealth of experimental data for the understanding of physical processes relevant for Earth's atmosphere and climate. The role of natural as well as anthropogenic climate forcing factors is assessed. CLOUD contributes to reduce uncertainty in climate modeling and give scientifically based input for political decision making on climate change adaptation and mitigation process.

The CLOUD results received considerable public attention by hundreds of reports, newspaper articles, blogs, etc. after the *Nature* publication, including coverage by *BBC*, *Wall Street Journal*, *Neue Zürcher Zeitung, Frankfurter Allgemeine Sonntagszeitung*, *Nature Geoscience* and *Nature Climate Change*.