THE MAGIC ROCKET CAMPAIGN: AN OVERVIEW

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ABSTRACT. Meteoric material entering the Earth's upper atmosphere is thought to give rise to a global layer of smoke particles in the mesosphere. These particles have been suggested to play a key role for noctilucent clouds, polar mesosphere summer echoes, charge balance, and neutral chemistry. The MAGIC campaign was conducted from Esrange in January 2005 to address fundamental questions about these smoke particles. A basic objective was to sample the particles and to take them to the laboratory for further analysis. In order to relate the particle distribution to the atmospheric circulation, also detailed measurements on atmospheric dynamics and related parameters were an integral part of the campaign. In this paper, we give an overview of the MAGIC campaign and the basic ideas behind it.

1. INTRODUCTION

Estimates of the amount of meteoric material entering the Earth's atmosphere vary between 10 and 100 tons per day [1, 2]. Most of the incoming meteoroid particles are of sub-millimetre sizes [3]. While particles smaller than approximately 20 µm can survive entry mostly intact as micrometeorites, larger particles are thought to vaporise in the 70-110 km altitude region. It is well known that this vaporisation is the source of metal atoms and ions that are frequently observed by lidars in the upper atmosphere. However, the subsequent evolution of the meteoric material is mostly conjecture. Chemical conversion, re-condensation and coagulation of the evaporated species is thought to form tiny 1-10 nm particles, denoted as "meteoric smoke" [4]. A scheme of the suggested fate of meteoric material in the mesosphere is shown in Fig. 1.

Meteoric matter has been found in the stratospheric aerosol below 40 km [5] and in Greenland ice cores [6]. In the mesosphere, there is indirect evidence for the existence of smoke particles e.g. from the measurement of heavy charge carriers [7]. However, there are currently no direct measurements of either the smoke or surviving micrometeorites between the stratosphere and the upper mesospheric source region. Despite of this fact, meteoric smoke has been proposed as a key player in the generation and evolution of several mesospheric phenomena:

- Smoke particles may provide condensation nuclei for ice particles involved in noctilucent clouds (NLC) and polar mesosphere summer echoes (PMSE), which occur at high latitudes during summer [8].

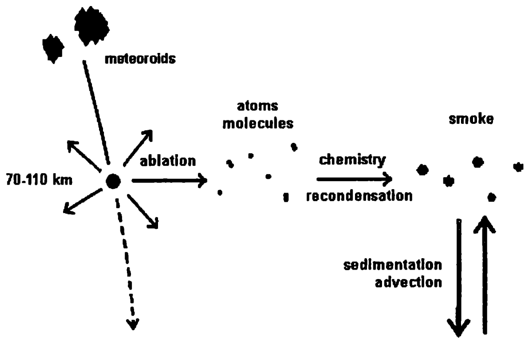

Fig. 1. Schematic of the fate of meteoric material in the mesosphere.

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- Smoke particles have been suggested as a surface for heterogeneous chemistry in the mesosphere. This is of particular interest in connection with the mesospheric water budget [9].
- Smoke particles may be important as (temporary) sink in the mesospheric metal budget by scavenging various metal species from the gas phase [10].
- Metallic clusters and particles may play a significant role in the mesospheric charge balance and related ionospheric phenomena [11].

Despite this potential importance of smoke particles, our knowledge about their properties is so far mostly theoretical. The most complete discussion of the mesospheric fate of meteoric material has been given by Hunten et al. [4]. The MAGIC project (Mesospheric Aerosol – Genesis, Interaction and Composition) aims to go beyond these ideas. The objective of MAGIC is to quantitatively answer fundamental questions about the properties of smoke in the mesosphere:

- Do re-condensed smoke particles of meteoric origin exist in the mesosphere?
- What is their number density and size distribution?
- What is the spatial distribution of the particles and how are they transported?
- What is the elemental and molecular composition of the particles?
- How do the particles interact with their mesospheric and ionospheric environment.

2. THE MAGIC IDEA

The *in situ* detection of neutral nanometre-size particles is difficult. They are too small for optical detection and their momentum is not sufficient to produce electrical pulses upon impact. A way to obtain maximum information about particle properties is direct sampling. The basic idea of MAGIC has been the development of an instrument and analysis techniques that for the first time allow us to bring smoke particles from the mesosphere into the laboratory and to study their properties in detail. The MAGIC campaign at Esrange in January 2005 was the result of close international collaboration and joined Swedish and U.S. funding efforts. In early 2002, NASA approved the MAGIC project with Frank Giovane at the Naval Research Laboratory (NRL) as Principal Investigator. The MAGIC particle samplers have subsequently been developed at NRL in close collaboration with Swedish and German scientists. In 2003, the Swedish National Space Board approved the MAGIC rocket campaign from Esrange, aiming at the first sampling of smoke particles in the mesosphere.

2.1. Particle Sampling

As nanometre-size particles tend to follow the airflow around payload structures, aerodynamic considerations are of critical importance for MAGIC [12, 13]. A basic idea of the instrument development has been to minimize aerodynamical perturbations by reducing the detector size. This resulted in an instrument design with sampling areas of diameter 3 mm located on the top of pins that are ejected from the payload top. As described by Hedin et al. [14], detailed numerical studies of rarefied air flow and particle impact were performed to test this measurement concept. As an example, Fig. 2 shows that particles with radii as small as 0.2 nm impact on the sampling surface without significant deflection.

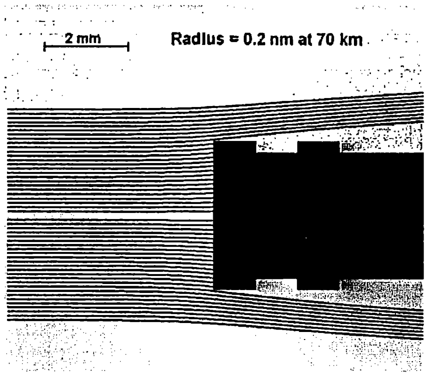

Fig. 2. The numerical simulation of particle impact onto the MAGIC sampling surface. Shown are trajectories of 0.2 nm smoke particles for flight conditions at an altitude of 70 km; the flow is from the left. See [14] for details.

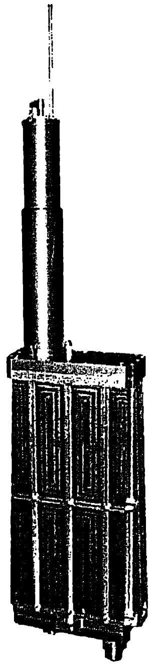

Fig. 3. The MAGIC flight instrument with an ejected sampling pin. The total length of the instrument without pin is 45 cm. Three of these instruments were flown on the MAGIC payload from Esrange.

The MAGIC flight instrument is shown in Fig. 3 with an ejected sampling pin. The sampling surface at the top of the pin is a standard carbon grid for transmission electron microscopy (TEM). The instrument contains nine sampling pins that are successively exposed during the mesospheric part of the rocket flight between 60 and 95 km. Exposure times of typically 5 seconds translate into a velocity-dependent altitude resolution of 3-5 km. Closing mechanisms keep the instruments vacuum-sealed before and after the mesospheric sampling sequence.

The analysis of the MAGIC smoke samples after recovery is carried out at varies international facilities. The primary analysis is based on detailed TEM studies at the Naval Research Laboratory. The TEM analysis can provide particle numbers, sizes, and shapes. In addition, by combining the TEM technique with energy-filtered imaging and energy-dispersive x-ray spectroscopy, the elemental composition of the samples can be investigated. The cosmic origin of the sampled material can be verified by radioactive isotope analysis, as carried out by gamma ray spectrometry at the Instituto Nazionale di Fisica Nucleare at Gran Sasso, Italy. Additional measurements are currently being planned in Sweden and Germany.

2.2 Model and laboratory efforts

In support of the MAGIC project, a number of modelling and laboratory studies are under way. Modelling studies concern both the detailed microphysics of smoke particle evolution and the global fate and transport of the meteoric material. These studies are carried out at the Naval Research Laboratory, Stockholm University, and the Leibniz Institute for Atmospheric Physics. Starting points are the microphysical Community Aerosol and Radiation Model for Atmospheres (CARMA) [15] and the NRL CHEM-2D chemical/transport model [16].

Laboratory studies on the generation and properties of smoke particles are performed at the University of East Anglia. Supporting laboratory investigations on the rocket-borne sampling of smoke are performed at various institutes in Germany (Table 1).

3. THE MAGIC CAMPAIGN

In order to study smoke particles in the mesosphere, all related processes must be addressed by co-ordinated experiments: smoke particle distribution, atmospheric structure and dynamics, as well as related neutral and charged species. After preparations in 2004, the MAGIC campaign took place at Esrange, Sweden, in January 2005 with comprehensive *in situ* and ground-based measurements. As the backbone of the campaign, the MAGIC rocket payload was launched on January 10 at 4:37 UT. Table 1 summarizes the scientific groups involved in the MAGIC project in general and in the MAGIC rocket campaign at Esrange.

As a complement to the local measurements, the MAGIC campaign was also coordinated with measurements of the Swedish Odin satellite. This is of particular interest when it comes to relating local data to large scale atmospheric motions [17].

3.1 Rocket and Balloon Measurements

The MAGIC rocket payload was equipped with three MAGIC particle samplers, an optical hygrometer for water vapour measurements from Stockholm University [18], and two charged particle detectors provided by the University of Colorado [19]. An Improved Orion motor carried the payload to an apogee of 95 km. Fig. 4 shows the instrument package consisting of the hygrometer and the MAGIC samplers. Positioned in an aerodynamically optimised geometry at the top of the payload, the MAGIC sampling sequence was carried out during the ascent part of the flight between 60 km and apogee. Water data was obtained both during ascent and descent.

In order to protect the instruments during landing, a retraction mechanism pulled the entire instrument package into the payload structure before parachute deployment. The recovery of the payload was complicated by harsh weather conditions and the presence of reindeers in the impact area. After heroic efforts of the recovery team on snow scooters, the payload was found in excellent condition 34 hours after the launch (Fig. 5).

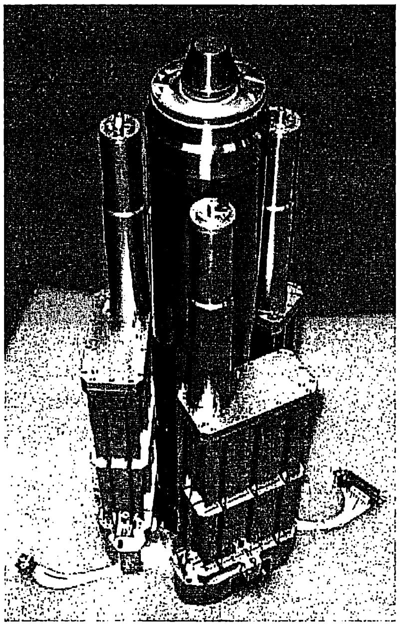

Fig. 4. The instrument package onboard the MAGIC rocket payload with the optical hygrometer in the centre surrounded by three MAGIC particle samplers.

Table 1. Research groups involved in the MAGIC campaign, the MAGIC instruments and related research efforts.

Research Group	Responsibility
Stockholm University (MISU), Stockholm, Sweden	scientific coordination of the MAGIC campaign
Naval Research Laboratory, Washington D.C., USA University of Florida, Gainesville, Florida, USA	development and preparation of MAGIC particle samplers
University of Colorado, Colorado, USA	charged particle detectors
Stockholm University (MISU), Stockholm, Sweden	measurement of water vapour from rocket and balloon
Swedish Space Corporation (SSC), Esrange, Sweden German Aerospace Center (DLR), Germany Leibniz-Institute for Atmospheric Physics, Germany	meteorological rockets for wind and turbulence
University of Bonn, Bonn, Germany Stockholm University (MISU), Stockholm, Sweden	RMR lidar measurements of temperature and density
Swedish Space Corporation (SSC), Esrange, Sweden	balloon measurements of temperature, density and winds
Institute for Space Physics (IRF), Kiruna, Sweden Swedish Space Corporation (SSC), Esrange, Sweden	ESRAD MST radar measurements
University of Bath, Bath, U.K. Institute for Space Physics (IRF), Kiruna, Sweden Swedish Space Corporation (SSC), Esrange, Sweden	SKiYMET meteor radar measurements of winds
Institute for Space Physics (IRF), Kiruna, Sweden Leibniz-Institute for Atmospheric Physics, Germany	EISCAT UHF and VHF ionospheric radar measurements
Swedish Space Corporation (SSC), Esrange, Sweden Stockholm University (MISU), Stockholm, Sweden	optical, ionospheric and geomagnetic monitoring
Naval Research Laboratory, Washington D.C., USA	MAGIC analysis by transmission electron microscopy
Instituto Nazionale di Fisica Nucleare, Italy	MAGIC isotope analysis
University of Jena, Germany Technical University Braunschweig, Germany Leibniz-Institute for Atmospheric Physics, Germany	laboratory analysis of particle impact
University of East Anglia, Norwich, U.K.	laboratory studies of smoke particles
Stockholm University (MISU), Stockholm, Sweden Naval Research Laboratory, Washington D.C., USA Leibniz-Institute for Atmospheric Physics, Germany	model studies of smoke particles
Chalmers University of Technology, Sweden Stockholm University (MISU), Stockholm, Sweden	Odin satellite measurements of water and temperature

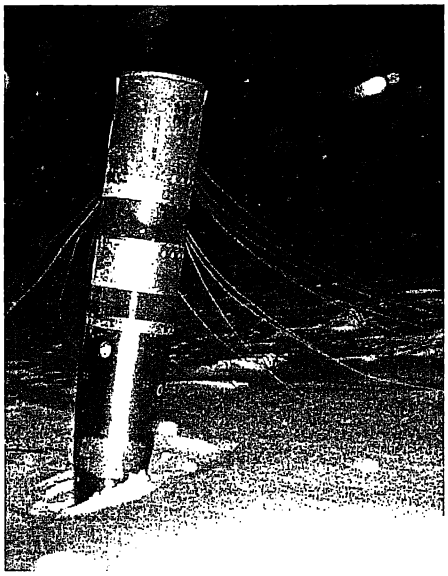

Fig. 5. The MAGIC payload as found by the recovery team. (Photo by Thomas Karlsson, Swedish Space Corporation.)

In order to obtain *in situ* wind measurements in the mesosphere, meteorological Superloki rockets (two with chaff, one with datasonde) were launched within the salvo at 3:29, 6:00 and 7:03 UT. A stratospheric balloon was launched at 3:13 UT, carrying a balloon version of the Stockholm hygrometer as well as temperature and density measurements. Fig. 6 shows preliminary results from the water vapour analysis. The combination of rocket and balloon hygrometer provides a water profile throughout the middle atmosphere. As shown in connection with earlier hygrometer flights from Esrange, water vapour is an excellent tracer for transport processes in the winter middle atmosphere [17].

3.2 Dynamical Analysis

Atmospheric dynamics is of central importance for the MAGIC project. Fiocco and Grams were first to point out the potential role of global transport for the distribution of meteoric material in the atmosphere [20]. Particular new interest exists in the efficiency downward transport inside the winter polar vortex [6]. A major MAGIC objective is therefore to relate the distribution of meteoric material to middle atmospheric transport processes. To this end, the particle sampling will be co-analysed with detailed meteorological data, in situ measurements of wind and water vapour, as well as the ground-based data listed in Table 1.

From the dynamical point of view, the position of Esrange is of particular interest for the MAGIC campaign. Being located near the edge of the winter polar vortex, horizontal gradients in the middle atmosphere provide good opportunities to study effects of transport on atmospheric composition. Indeed, dynamic conditions in the middle atmosphere were significantly disturbed during the campaign with frequent changes between cold and warm air masses above Esrange. Fig. 7 shows the temperature structure with a stratospheric warming during the launch night as obtained by the combined measurements of lidar and balloon.

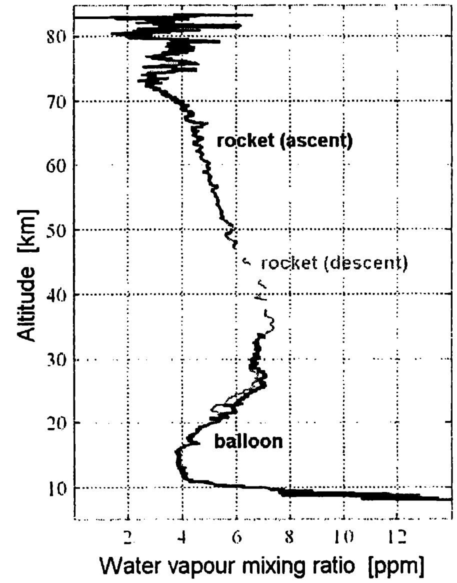

Fig. 6. The middle atmospheric distribution of water vapour during the launch night as measured by the hygrometers from Stockholm University onboard the MAGIC rocket payload and the stratospheric balloon.

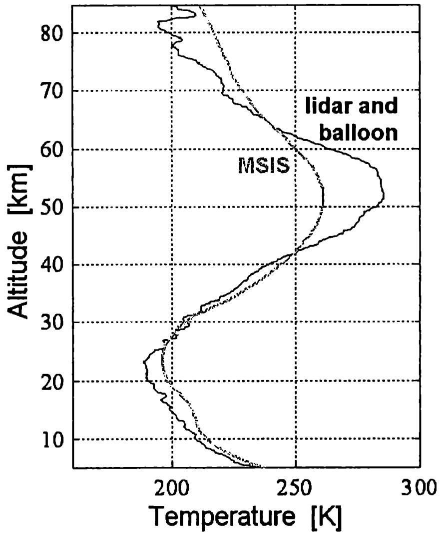

Fig. 7. The temperature profile above Esrange during the launch night as measured by the University of Bonn RMR lidar and the stratospheric balloon. Comparison with the MSIS profile shows the presence of an upper stratospheric warming.

4. OUTLOOK

The MAGIC rocket campaign from Esrange in January 2005 featured the first flight of MAGIC particle samplers for the direct measurement of meteoric smoke particles. The campaign has also provided comprehensive sets of *in situ* and remote sensing data on the background state and the dynamics of the atmosphere. The currently ongoing analysis of the MAGIC campaign is coordinated by NRL and MISU. Detailed scientific results will be published in the near future.

A basic idea of the MAGIC concept is to enable studies of meteoric smoke particles in a variety of atmospheric conditions. The MAGIC particle samplers have been designed as self-consistent instruments that are easy to incorporate into different sounding rocket payloads. A second MAGIC flight has already been carried out in mid-latitude conditions from Wallops Island, Virginia, USA, in May 2005. A third flight of MAGIC instruments is scheduled for March 2006 as part of the German/Norwegian ECOMA project from Andøya, Norway.

Of particular interest are MAGIC particle measurements in connection with scientific questions related to mesospheric chemistry and to mesospheric ice (noctilucent clouds, polar mesosphere summer echoes). Future MAGIC launches focussing on these topics have recently been proposed.

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