Scattering, Clouds & Climate: A Short Workshop of Exploration

Mathematical Institute, University of Oxford

24th - 25th March 2014

UNIVERSITY OF OXFORD

OCCAM
OXFORD CENTRE FOR COLLABORATIVE APPLIED MATHEMATICS

Workshop aims

- Bring together mathematicians and atmospheric physicists researching scattering of electromagnetic radiation by atmospheric ice crystals.
- Identify areas where advances in mathematical methods may be useful in climate modelling applications.
- Nucleate future collaborative efforts.

Workshop format

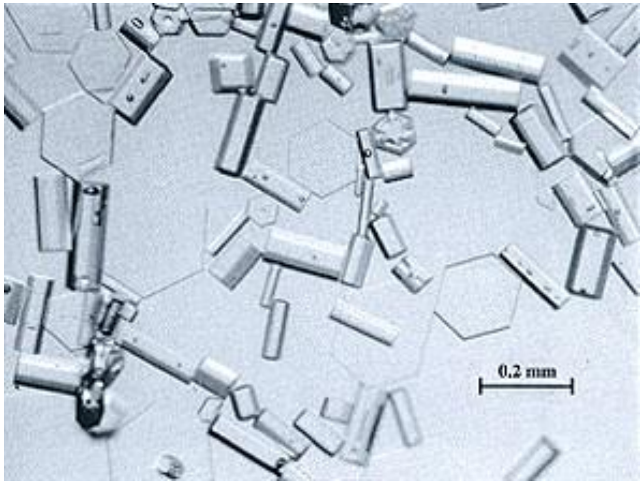
- “Workshop” not a “conference”
- Talks 30 mins + 10-15 mins for questions/discussion
- Please ask/take questions during talks!
- Two scheduled discussion sessions

Programme for Monday

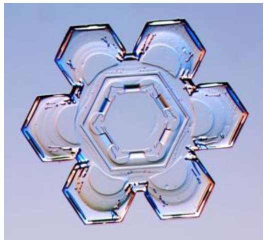
1300-1400	Lunch and registration
1400-1415	Welcome and introduction
1415-1545	Talks
1545-1615	Tea/coffee
1615-1745	Talks
1745-1830	Discussion
1830-1900	Free time (opportunity to check in at Somerville College)
1900	Reception and dinner at Somerville College

Ice particles in clouds

- Atmospheric ice crystals can form over a wide range of temperatures – from just below 0°C to ≈-80°C
- Generally, the colder the cloud, the smaller the crystals (less water vapour available, inefficient dissipation of latent heat)
  - In coldest clouds crystals may be 100µm or smaller
  - In warmer clouds crystals may grow to a few mm in size
- Simplest forms are solid ice hexagonal prisms…



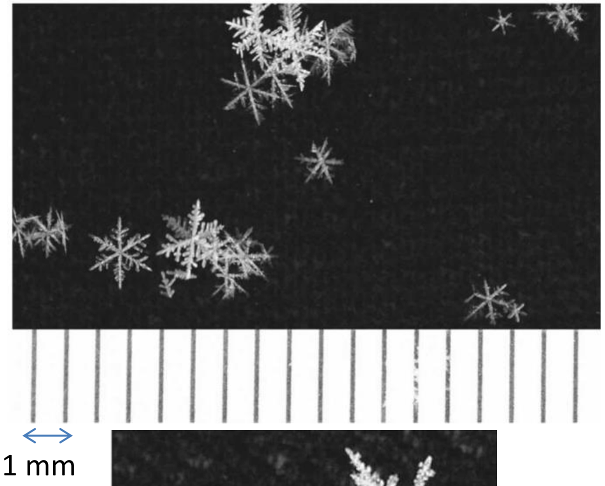
From Atmospheric Halos by Walter Tape
ISBN 0-87590-834-9

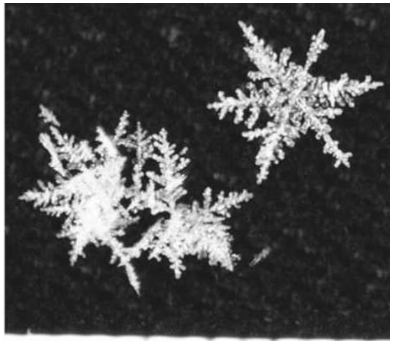


From www.snowcrystals.com

… but not all ice crystals are that simple!

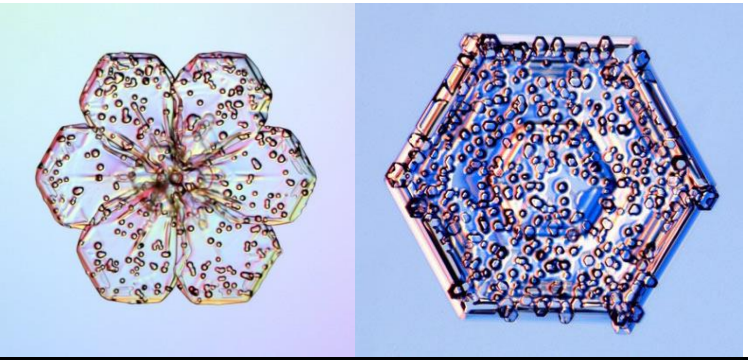
- Once large enough, the crystals start to fall through the atmosphere. They can collide with other crystals to form large complex aggregates up to 1cm in size



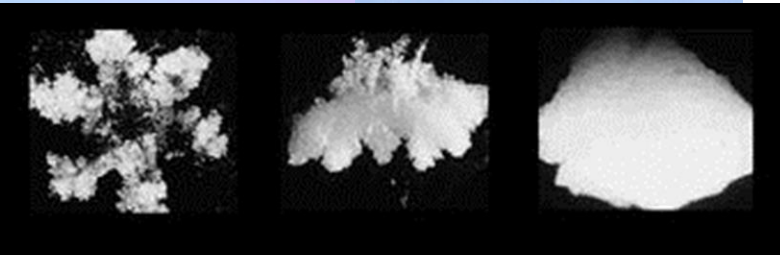


From Brandes et al 2008 J. Appl. Met. & Clim.
http://dx.doi.org/10.1175/2008JAMC1869.1

From www.snowcrystals.com



- They can also collide with supercooled droplets which freeze on their surface (eventually leading to hail)



Riming of an ice crystal in a supercooled wind tunnel, leading to graupel / small hail

Why care about E-M scattering by ice particles?

1. Radiative Transfer

- Light from the sun ("shortwave" radiation 0.2 – 4 μm wavelength) is scattered by ice clouds, some reflected back to space (cooling effect)
- Infrared light is emitted from the earth ("longwave" radiation 4 – 100 μm wavelength) – scattered and absorbed by ice clouds, some is scattered/reemitted back to the surface (warming effect)
- Overall effect on climate: longwave warming wins in a global average sense – but individual clouds may warm or cool us. Can we predict this from the number, size and shape of the crystals in the cloud?

Anthony Baran
Steven Dobbie
Joseph Ulanowski
Evelyn Hesse
Helen Smith
Paul Connolly
Juliet Pickering
Cathryn Fox
Robin Hogan

Why care about E-M scattering by ice particles?

2. Remote Sensing

- Measure electromagnetic waves scattered by ice particles to infer the microphysics of the particles (number, size, shape)
- Two types:
  - "Active" = radar, lidar. Generate a short pulse of light, and then listen for echo. Backscattered wave (power and polarisation) tells you something about the ice particles.
  - "Passive" = radiometers. No transmission of waves, rely on either scattering of sunlight, or emission from particles
- Wavelengths from 10 cm to 0.3 µm

David Bebbington
Robin Hogan
Caroline Poulsen
Joseph Ulanowski
Chris Westbrook
Anthony Baran
Thorwald Stein


Chilbolton radar
- from www.stfc.ac.uk


MODIS satellite (NASA)

Why care about E-M scattering by ice particles?

Joseph Ulanowski
Chris Westbrook
Steven Dobbie

3. Optical effects

- Ice particles can scatter sunlight to form amazing optical phenomena (arcs and halos)
- Some effects well understood (eg circumzenithal arc)
- Some are not understood at all (eg “odd-radius” halos) – need to understand from scattering theory what kind of crystals could cause these effects

NASA Earth Science Picture of the Day, April 06, 2012

From www.atoptics.co.uk/halo/pyredens.htm

Requirements for scattering calculations

- Particle span D relative to wavelength λ spans range from $D/\lambda \sim 0.001 - 1000$ depending on the problem - no single technique can be applied over this range
- 3D Maxwell not 2D Helmholtz
- Need to be able to handle transmission (ice is a dielectric, not a conductor), and ideally absorption
- Want the *far-field, single scattering* pattern (cloud is dilute; multiple scattering can be important, but can be dealt with using this information and a RT model)
- At minimum need to handle a hexagonal prism. Ideally flexible geometry to deal with complex particles
- Mostly off-line calculations – then we integrate over size/shape distributions / create look up tables. So need to be able to solve a problem using a realistic computer spec, but doesn't necessarily need to be super-fast

Typical tools

- $D/\lambda \sim 0.001 - 10.$
  - Mie theory or T-matrix ~ rigorous derivation from Maxwell's equations, computationally efficient, but practically very difficult to apply beyond highly symmetrical shapes such as spheroids (so approximate real shape by a simplification)
  - Discrete Dipole Approximation (DDA) ~ treat scatterer as a matrix of small, polarisable dipoles. Physically intuitive, completely flexible geometry. Computationally expensive for large, intricate particles (CPU and memory).
  - Less common approaches:
    - Rayleigh-Gans approximation (aka Born approximation) ~ essentially first order version of DDA with no coupling between dipoles – reduces to simple sum of interference terms (Robin Hogan later)
    - Fredholm Integral method (see David Bebbington's talk later)
    - Generalized Multiparticle Mie-Solution (group at Penn State)

Typical tools

- $D/\lambda \sim 10 - 1000.$
  - Geometric optics ~ high frequency limit: trace light rays along straight line paths using Monte Carlo approach. Flexible geometry. Assumes all facets flat on scales of order the wavelength (often not OK!). Not clear exactly how to account for diffraction. Various kluges to deal with these two problems. Simple and cheap on memory.
  - Finite Difference Time Domain ~ very computationally expensive, but more rigorous in the sense that are now solving Maxwell's equations proper. Need a very big computational domain to simulate far-field, but fine mesh for short wavelength. Only really practical at the lower end of this D/λ range.

Some possible collaboration points?

- Development of new ideas / numerical tools to compute scattering properties
  - faster / less memory-intensive techniques (all D/λ values)
  - particular lack of options / rigour for $D/\lambda > 10$
  - ideas for how to deal with wavelength-scale "roughness" on particle surfaces at large D/λ
- Development / application of better software packages to do these calculations than are used in ice community at present
  - eg BEM++ ?
- Error analysis / convergence of numerical tools – often we simply use a tool and assume the results to be accurate. Is this OK?
  - Mathematical results for error bounds?
- Development of new measurement datasets to test the theoretical / numerical predictions (MICC, SID3, etc…)

Mathematical analysis of wave scattering

- Very **mature** field, but still an **active** research area in applied mathematics
- Acoustic, electromagnetic and elastic waves
- Time and frequency domains
- **Model problem** (frequency domain):

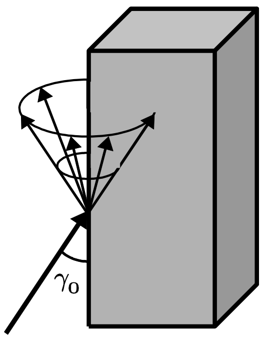
$$(\Delta + k^2)\mathrm{u} = 0$$

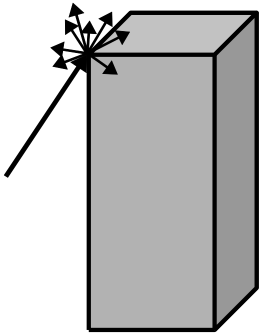
- What are people working on?

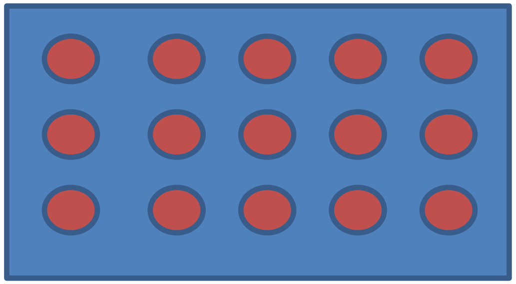
Analytical methods

David Abrahams
Jon Chapman
Samuel Groth
John Hannay
David Hewett
John Ockendon
Anthony Rawlins
Valery Smyshlyaev
John Wettlaufer

- High frequency asymptotics (Geometrical Optics, Geometrical Theory of Diffraction)
- Canonical problems (wedges, cones, ray tangency, concave-convex transition)
- Inhomogeneous media:
  - Composite materials
  - Homogenisation
  - Scattering at ice-water interface



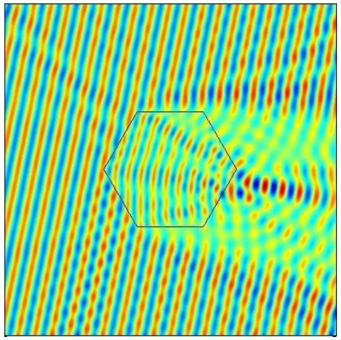


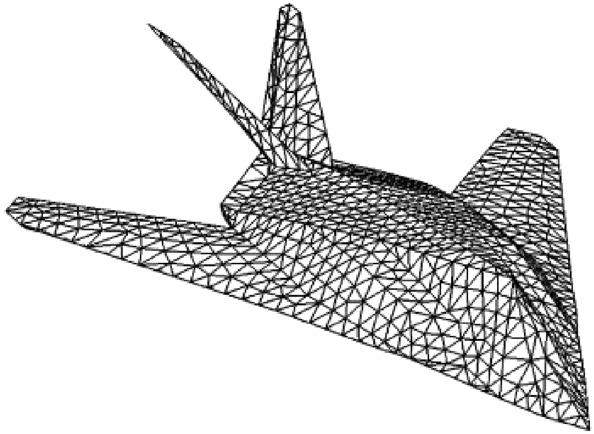


Numerical methods

Timo Betcke
Simon Chandler-Wilde
Andrew Gibbs
Ivan Graham
Samuel Groth
David Hewett
Stephen Langdon
Valery Smyshlyaev

- Development of new FEM/BEM formulations
- Error/stability analysis
- Fast implementations (e.g. BEM++)
  - Matrix compression (FMM, H-matrix)
  - Preconditioning
  - Domain decomposition
  - Parallelisation
- Rough surface scattering
- Inhomogeneous media





- Traditionally a low/mid frequency approach, but high frequency “hybrid numerical-asymptotic” methods are emerging

Some objectives

- **Understand the key issues** relating to ice scattering that currently limiting the accurate modelling of earth’s radiation balance
- Identify opportunities to **apply emerging mathematical tools** (computational and analytical)
- **Identify “model” and “challenge” problems** of relevance to application and of interest to mathematicians