3. Numerical simulation is based on partial differential equations (PDEs) that describe temporal & spatial variations of physical quantities such as density, velocity, pressure, and magnetic field.

e.g.)

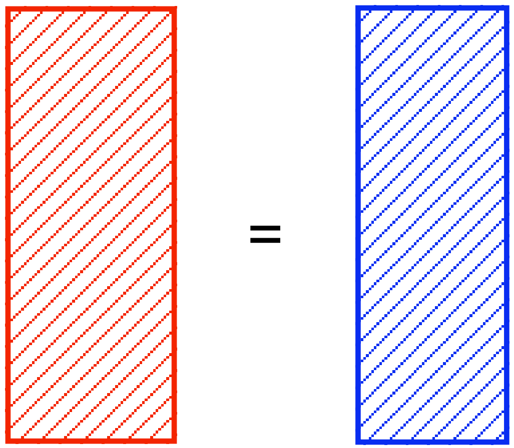
Magnetohydrodynamic equations... **a set of PDEs**

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{v})$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = -(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} + \frac{-\nabla p + \boldsymbol{j} \times \boldsymbol{B}}{\rho}$$

$$\frac{\partial p}{\partial t} = -(\boldsymbol{v} \cdot \nabla) p - \gamma p \nabla \cdot \boldsymbol{v}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$



Time-dependent part **Space-dependent part**

This set of PDEs describe temporal & spatial variations of physical quantities $\rho, \boldsymbol{v}, P, \boldsymbol{B}, \boldsymbol{j}$, which are given by functions of space (x, y, z) and time (t).

Why do we need numerical simulation?

Basic equations given by a set of PDEs are **complex; they are coupled with each other**.

$$\frac{\partial \rho}{\partial t} = -\nabla \bullet (\rho \boldsymbol{v})$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = -(\boldsymbol{v} \bullet \nabla)\, \boldsymbol{v} + \frac{-\nabla p + \boldsymbol{j} \times \boldsymbol{B}}{\rho}$$

$$\boldsymbol{j} = \frac{1}{\mu} \nabla \times \boldsymbol{B}$$

$$\frac{\partial p}{\partial t} = -(\boldsymbol{v} \bullet \nabla)\, p - \gamma\, p\, \nabla \bullet \boldsymbol{v}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$

Solving these equations analytically to **obtain** an **exact solution** is **difficult**.

Therefore, we **perform numerical simulation** to **obtain** an **<u>approximate solution</u>**, which **helps** to **understand** the **physical mechanism** of a phenomenon evolving in time and space.

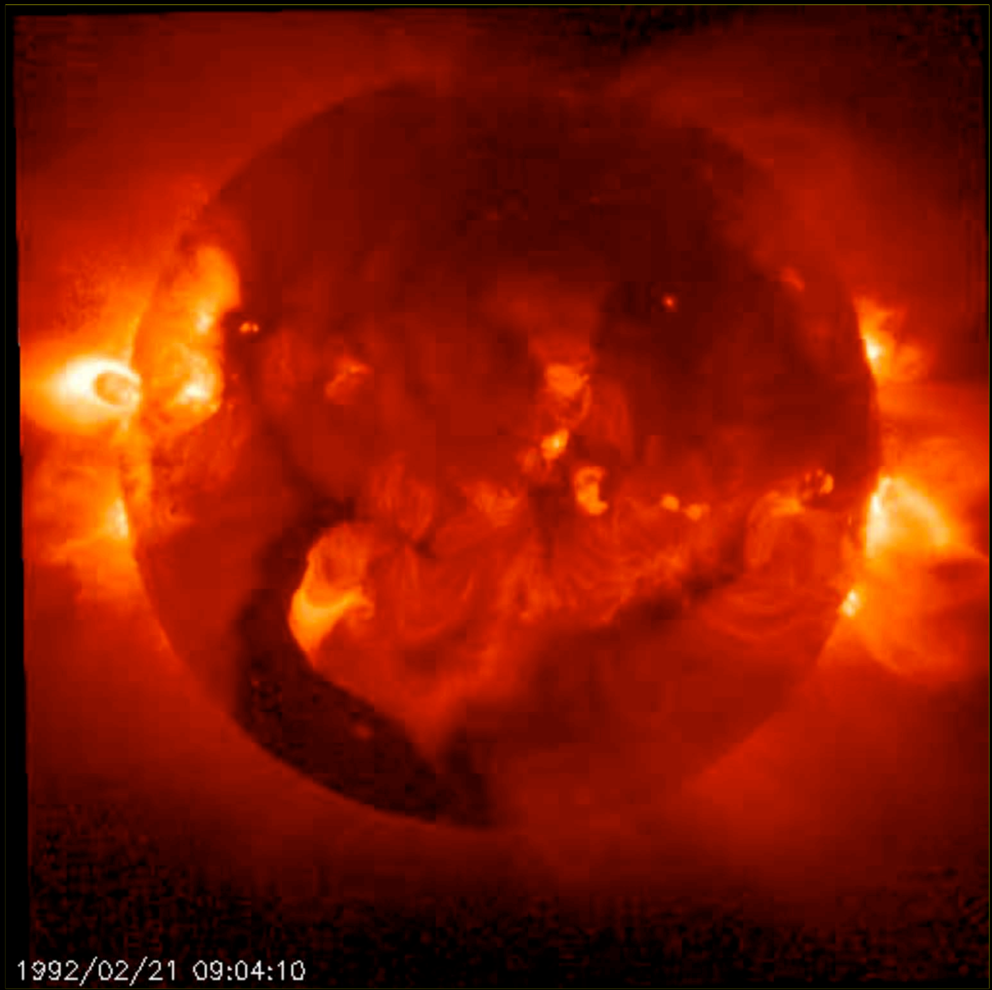
Examples

numerical simulations performed for investigating solar & space phenomena

Solar flare

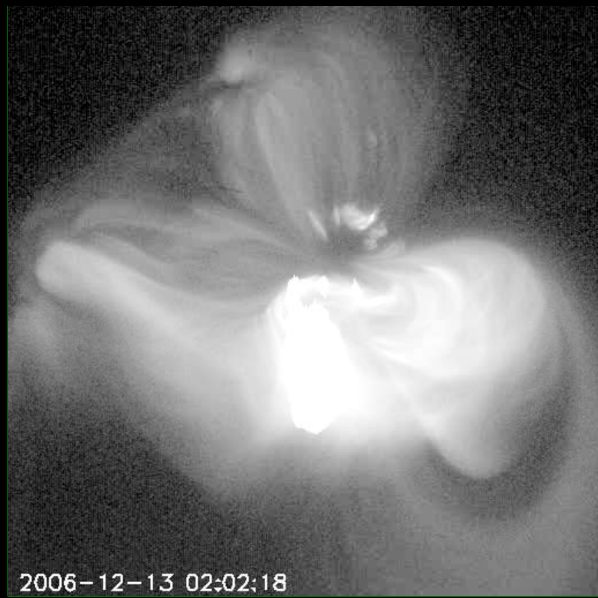
Explosive phenomenon in a solar corona

Observation of solar flares

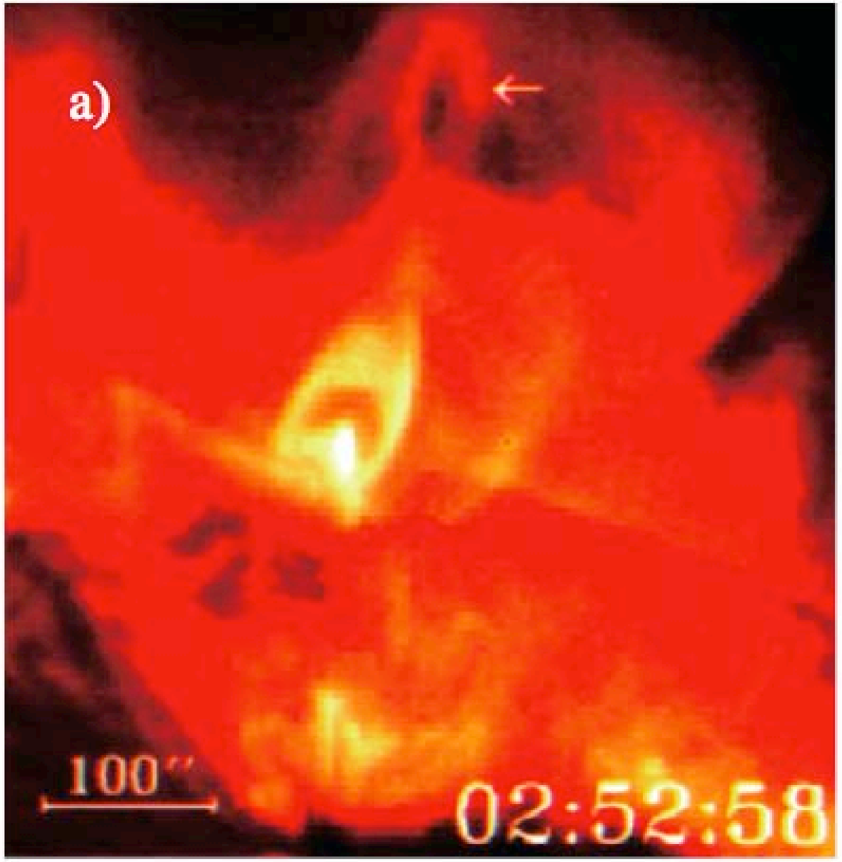


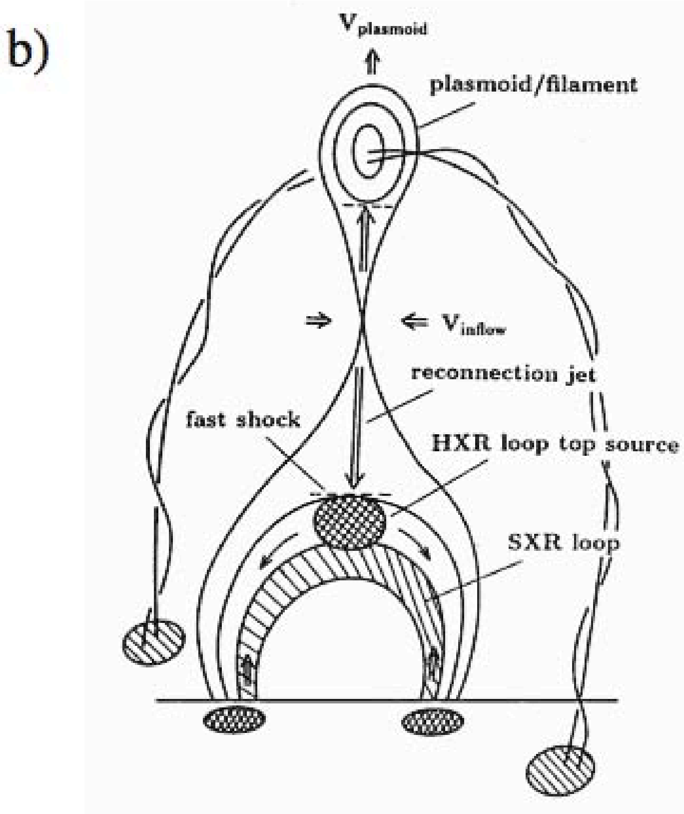
Full-disk image of a solar corona
(observed by ***Yohkoh*****)**

An X-class flare in an active region
(observed by ***Hinode*****)**



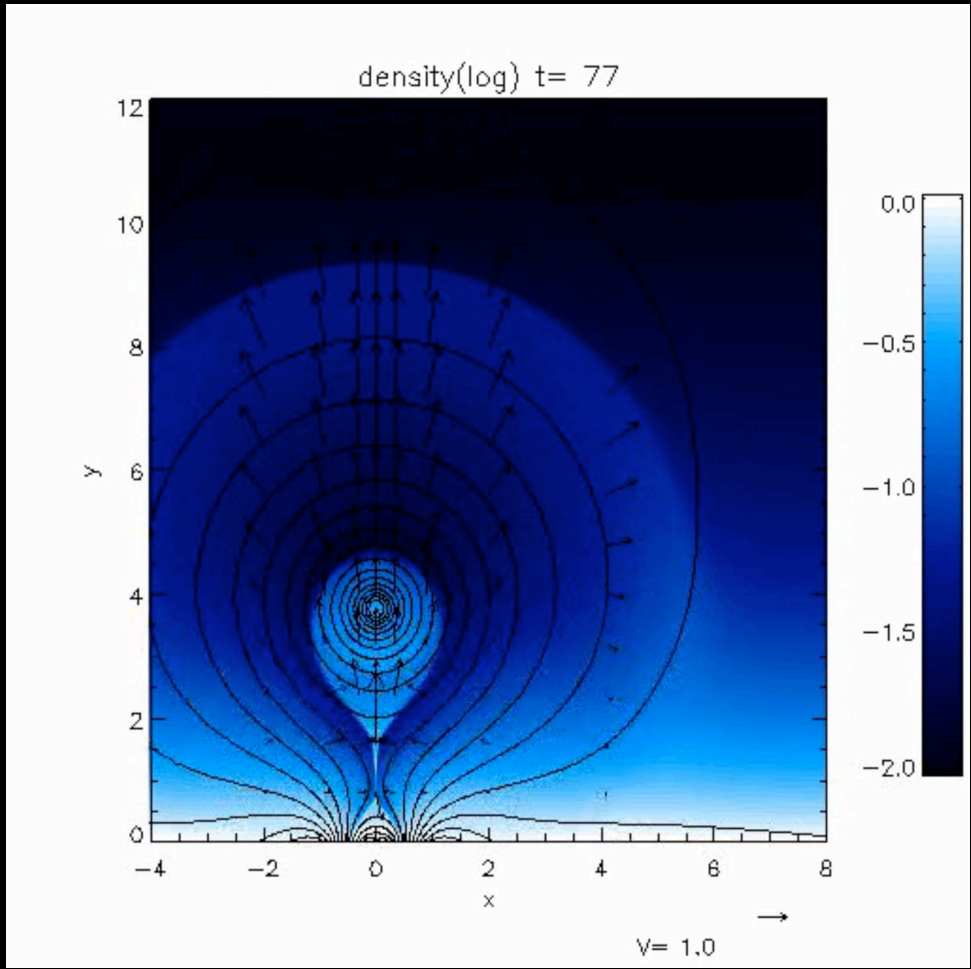
Schematic model of a solar flare





Shibata et al. (1995)

Numerical simulation of a solar flare

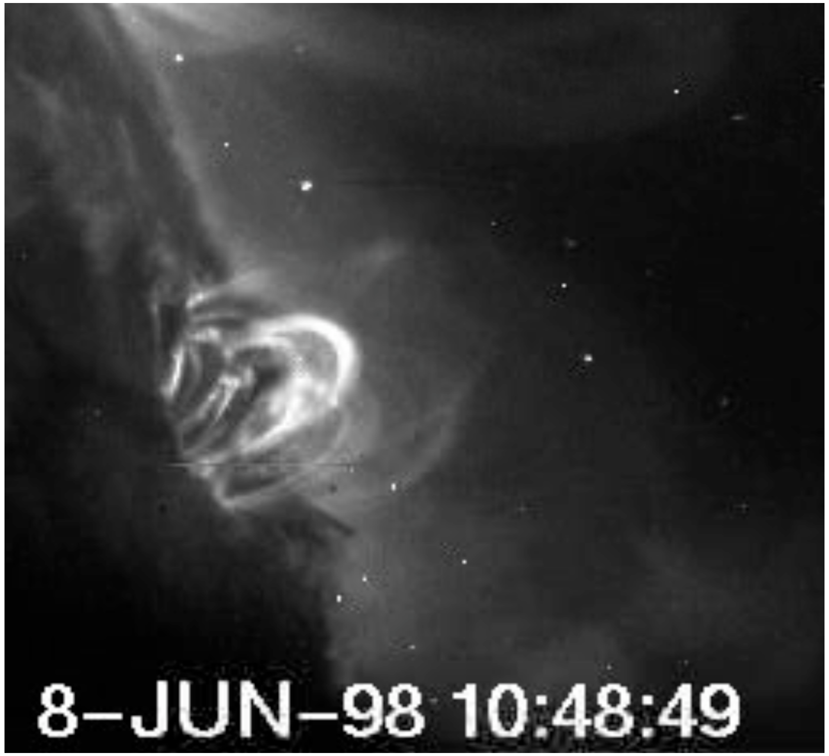


Shiota et al. (2005)

Flux emergence

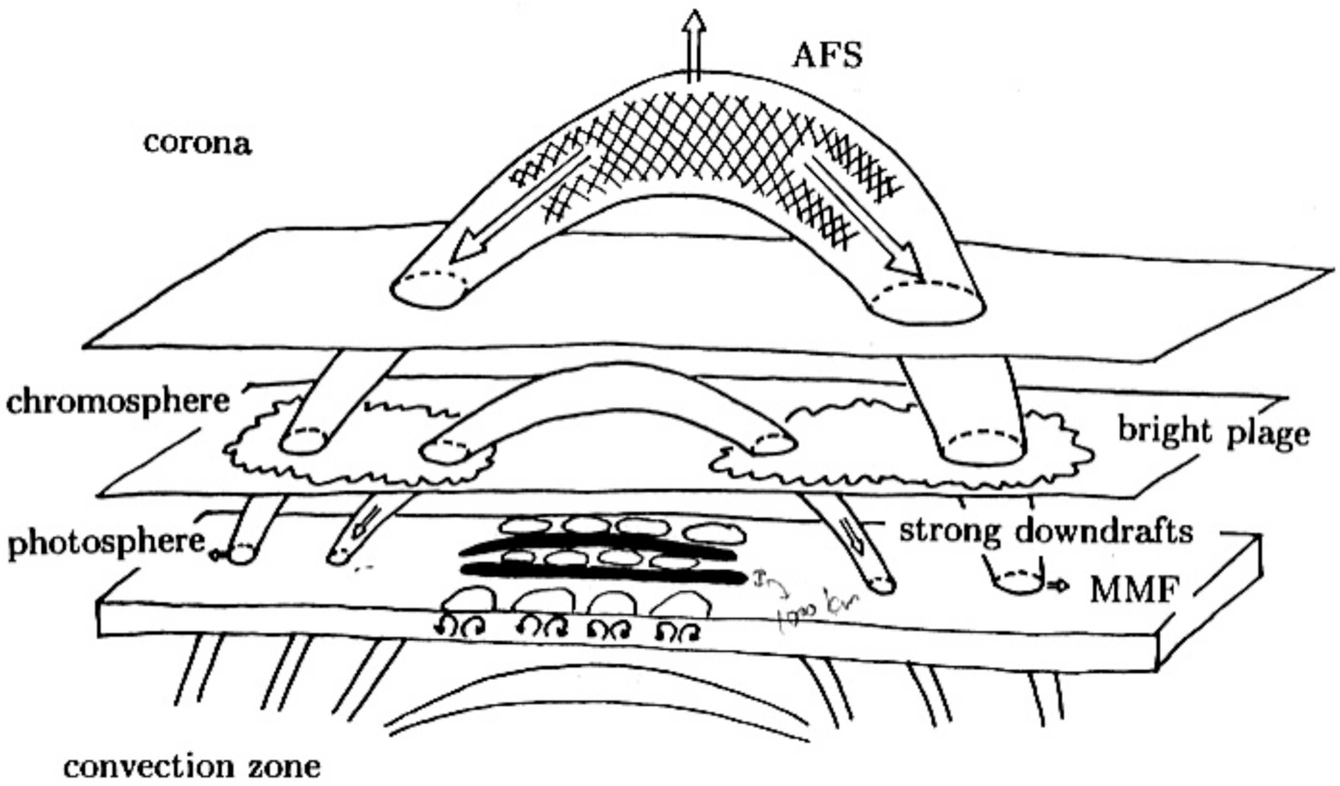
Emergence of magnetic flux from a solar interior into a solar atmosphere

Observation of flux emergence



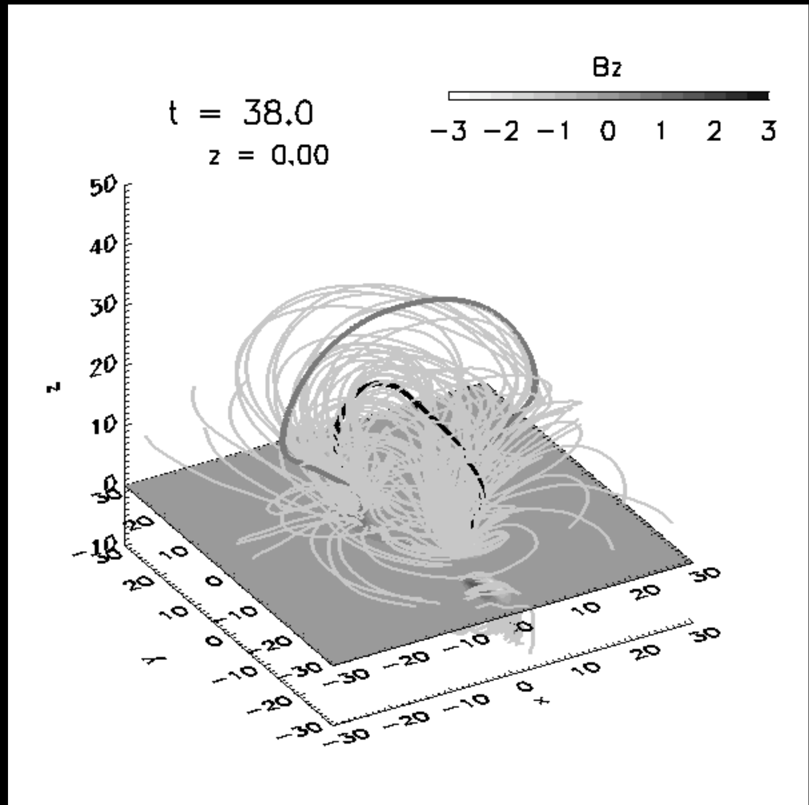
Observed by ***TRACE***

Schematic model of flux emergence



Shibata et al. (1989)

Numerical simulation of flux emergence

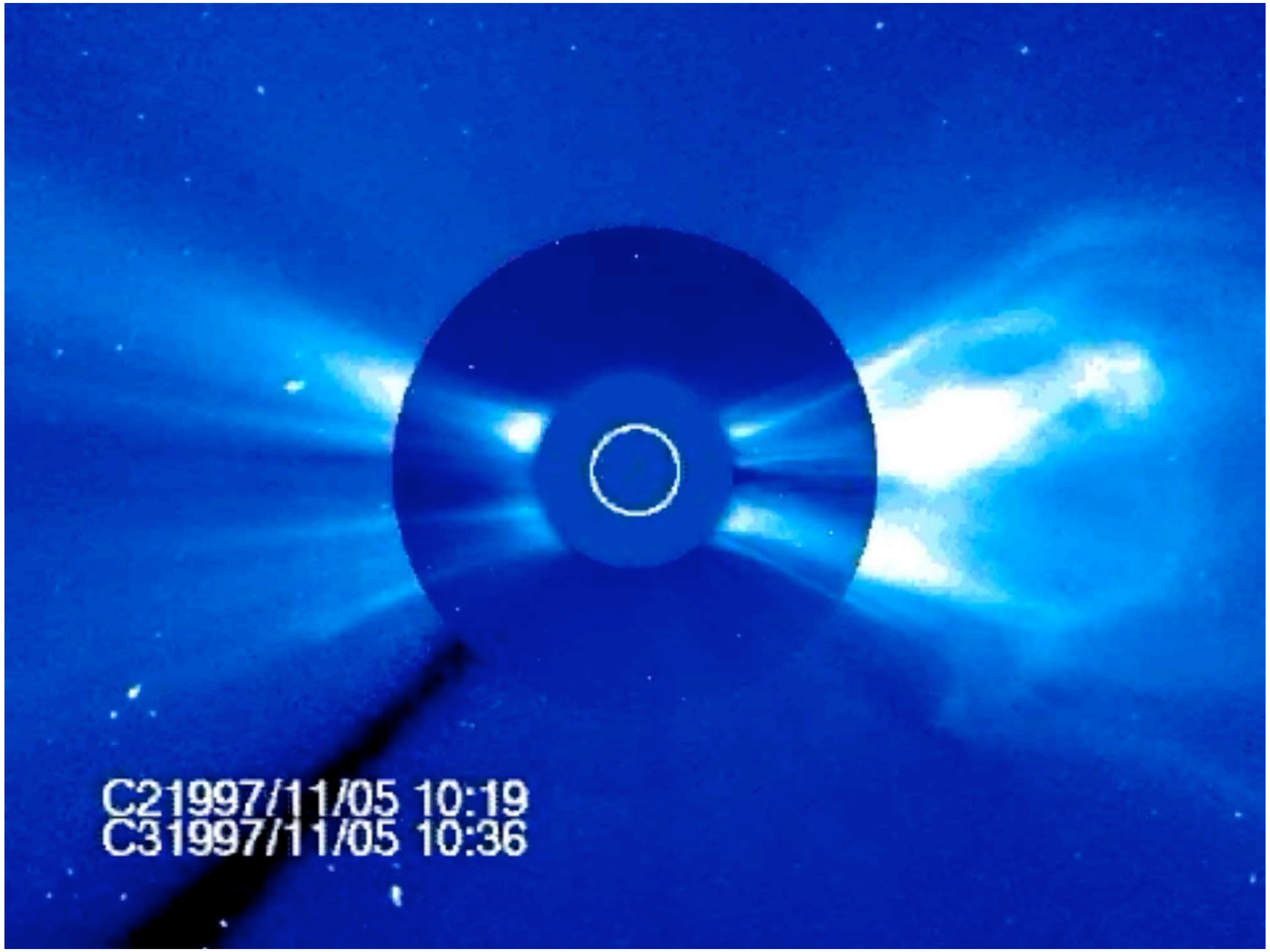


Magara (2004)

Coronal mass ejection

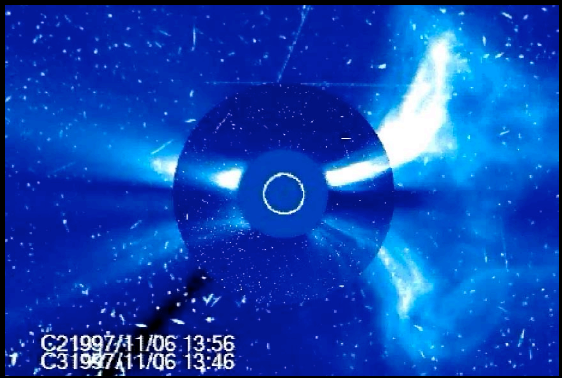
Solar global eruption to an interplanetary space

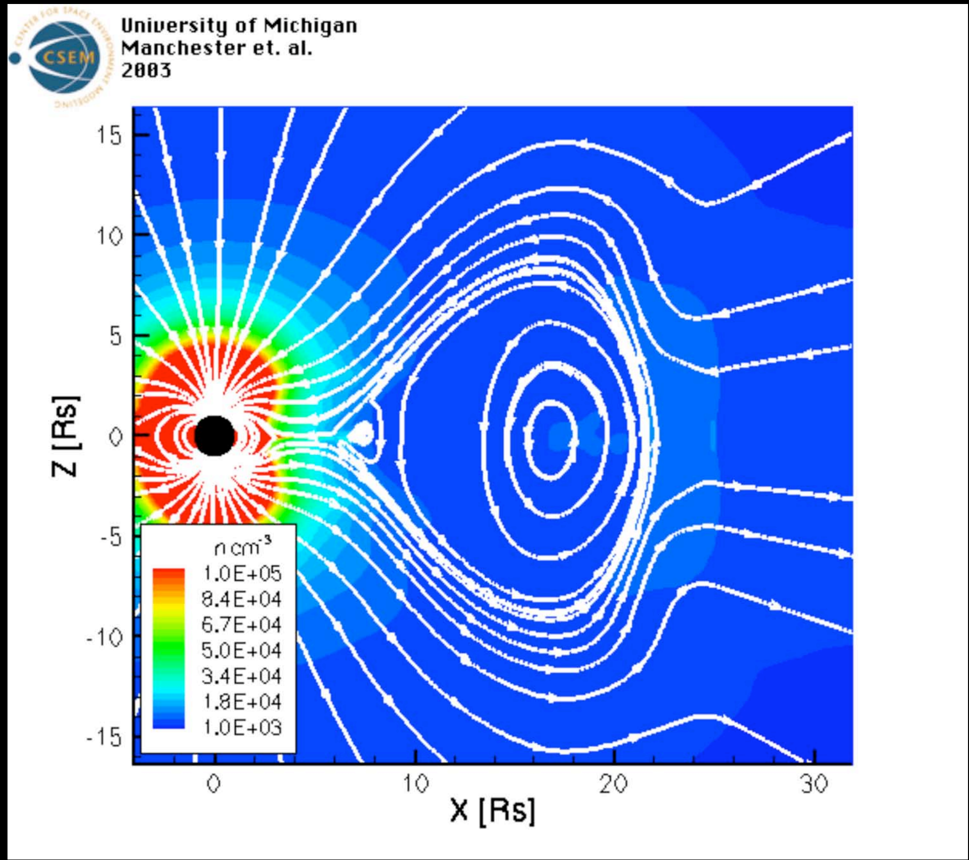
Observation of coronal mass ejections



Observed by ***SOHO***

Numerical simulation of a coronal mass ejection (from the Sun to the Earth)



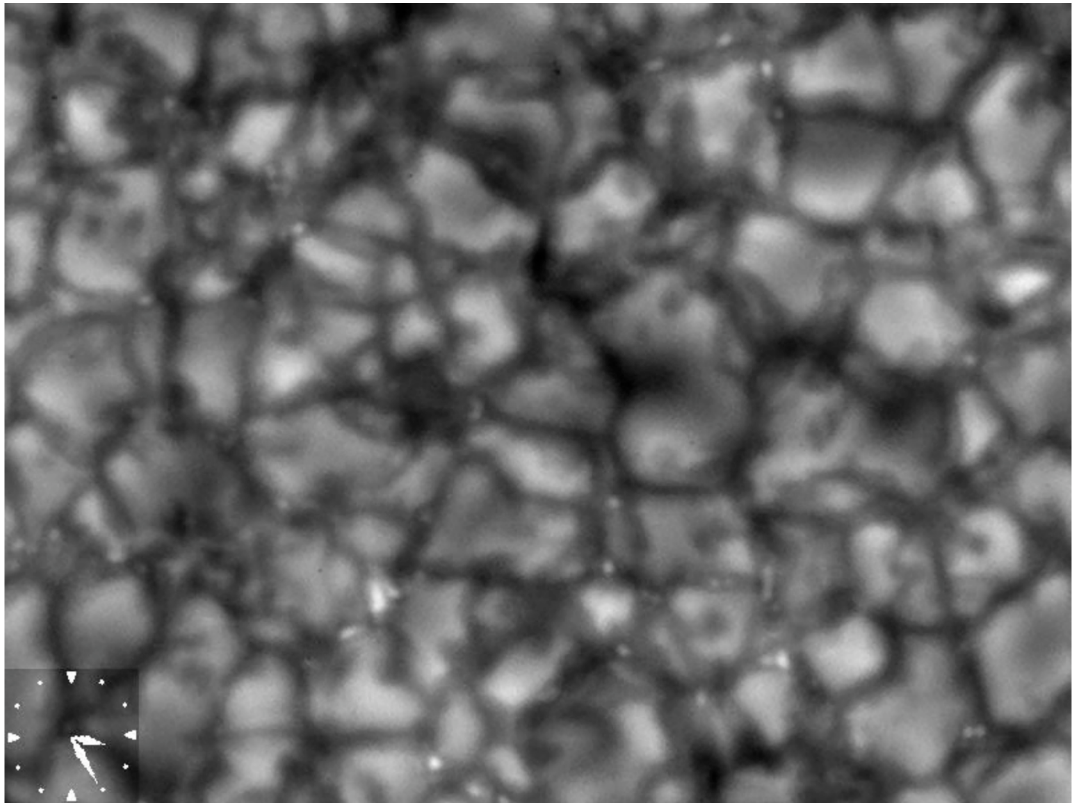


Manchester et al. (2003)

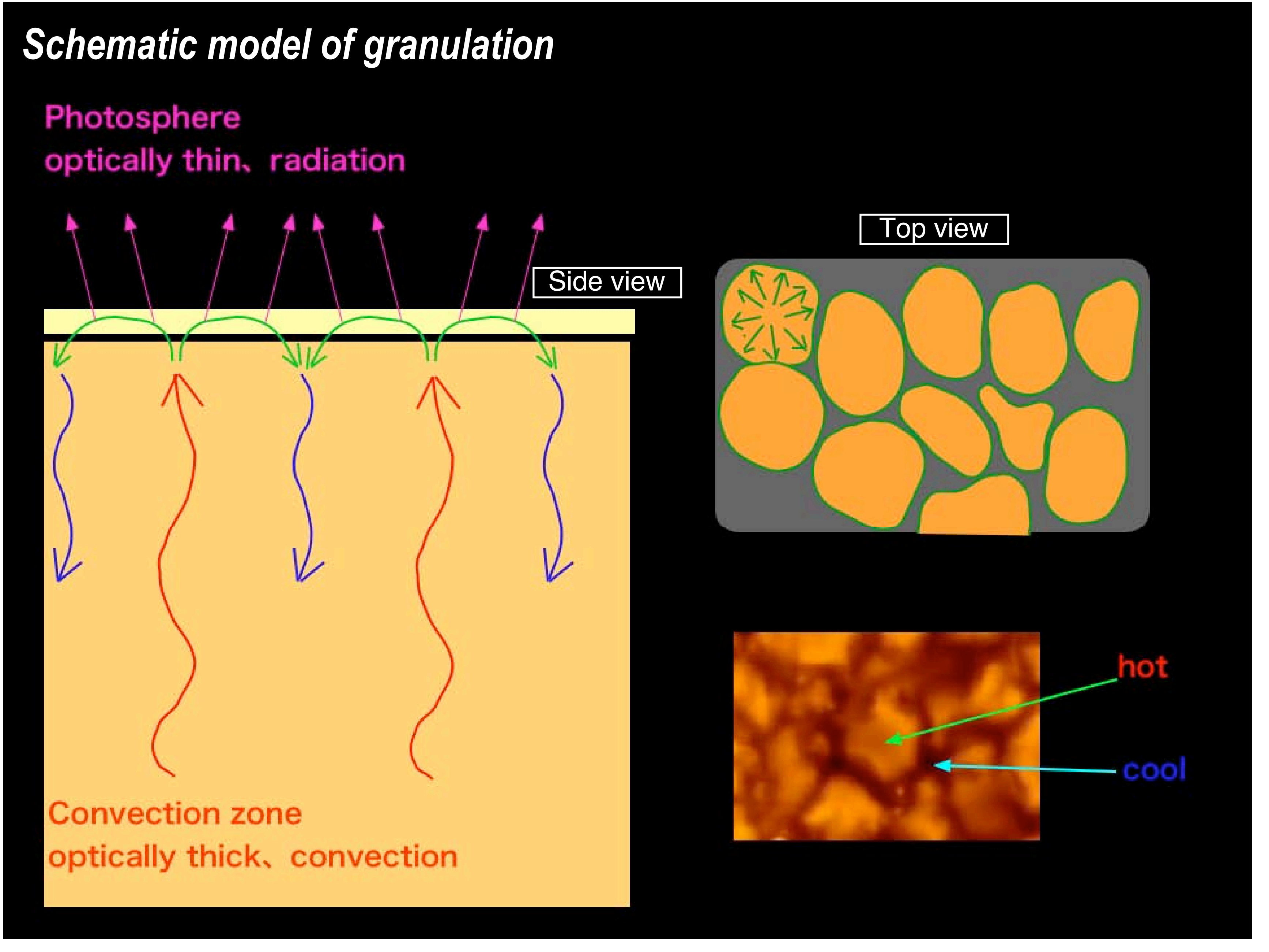
Granulation

Solar surface motion

Observation of granulation at a solar photosphere



Observed by ***Hinode***



Schematic model of granulation
Photosphere
optically thin、radiation
Side view
Top view
hot
cool
Convection zone
optically thick、convection

Numerical simulation of granulation