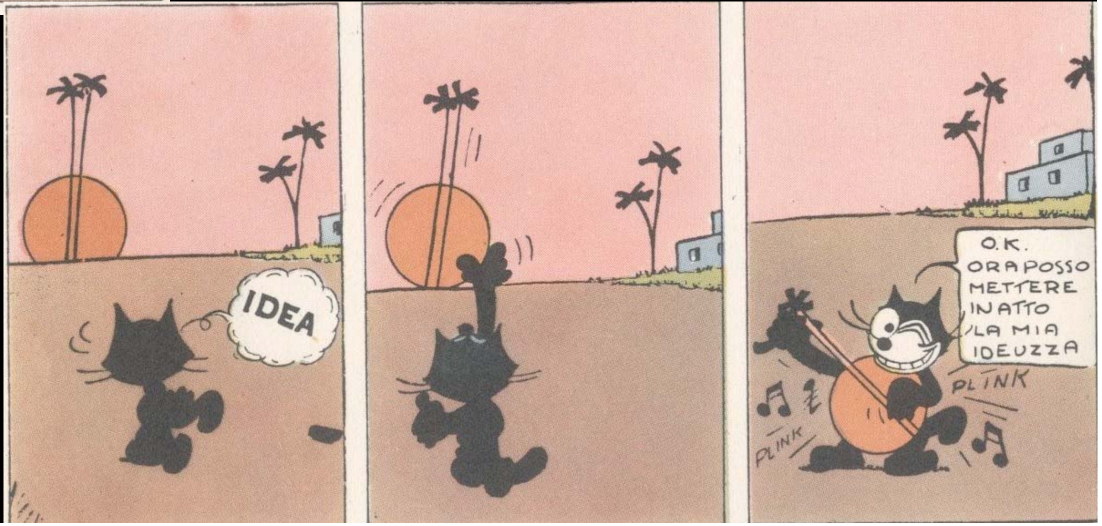
Il sole e le reazioni nucleari

2013.11.20

Stefano Sandrelli
INAF-Osservatorio Astronomico di Brera

Grazie a Fabio Pizzolato,
la cui presentazione
ho ampiamente saccheggiato



Parte I

2013.11.20 Il sole e le reazioni nucleari

un’istantanea del Sole

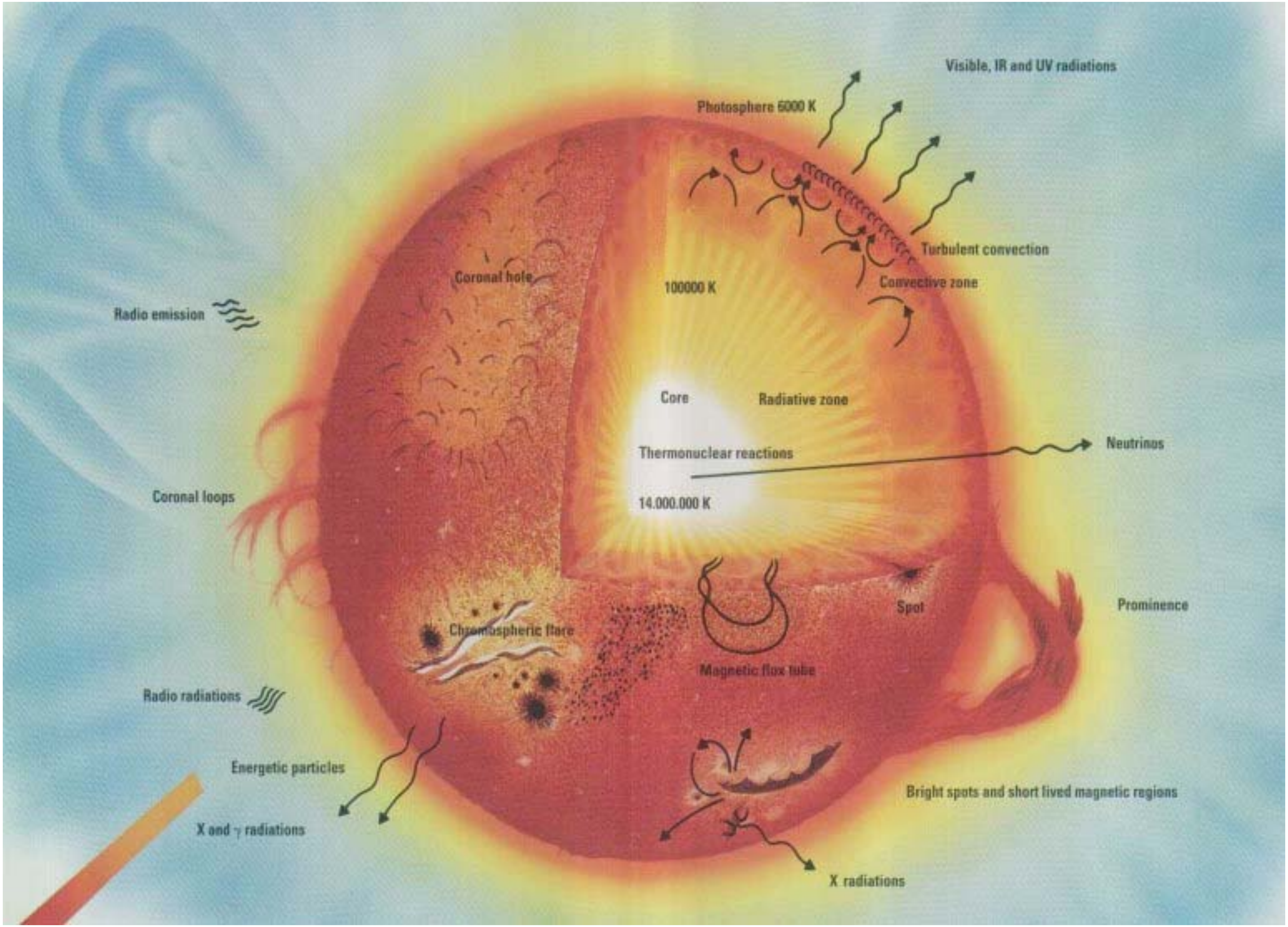
- http://www.nasa.gov/missions/current/index.html : tutte le missioni spaziali attive, con descrizioni e links alle loro pagine web: per il Sole vedi Hinode, Rhessi, Soho, Stereo, Trace, SDO
- http://spaceweather.com/ Informazioni in tempo reale sull'attività solare
- D. Whitehouse; Il Sole: una biografia; Mondadori (2007)
- U. Villante; Al di là delle nuvole, Bollati Boringhieri (2001)
- P. V. Foukal; Solar Astrophysics; Wiley (*)

Il Sole

- Distanza dalla Terra: 149.6 milioni di km
- Diametro: 1.3 milioni di km (109 volte la Terra)
- Massa: 2×10^{30} kg (330.000 volte quella della Terra)

Il Sole

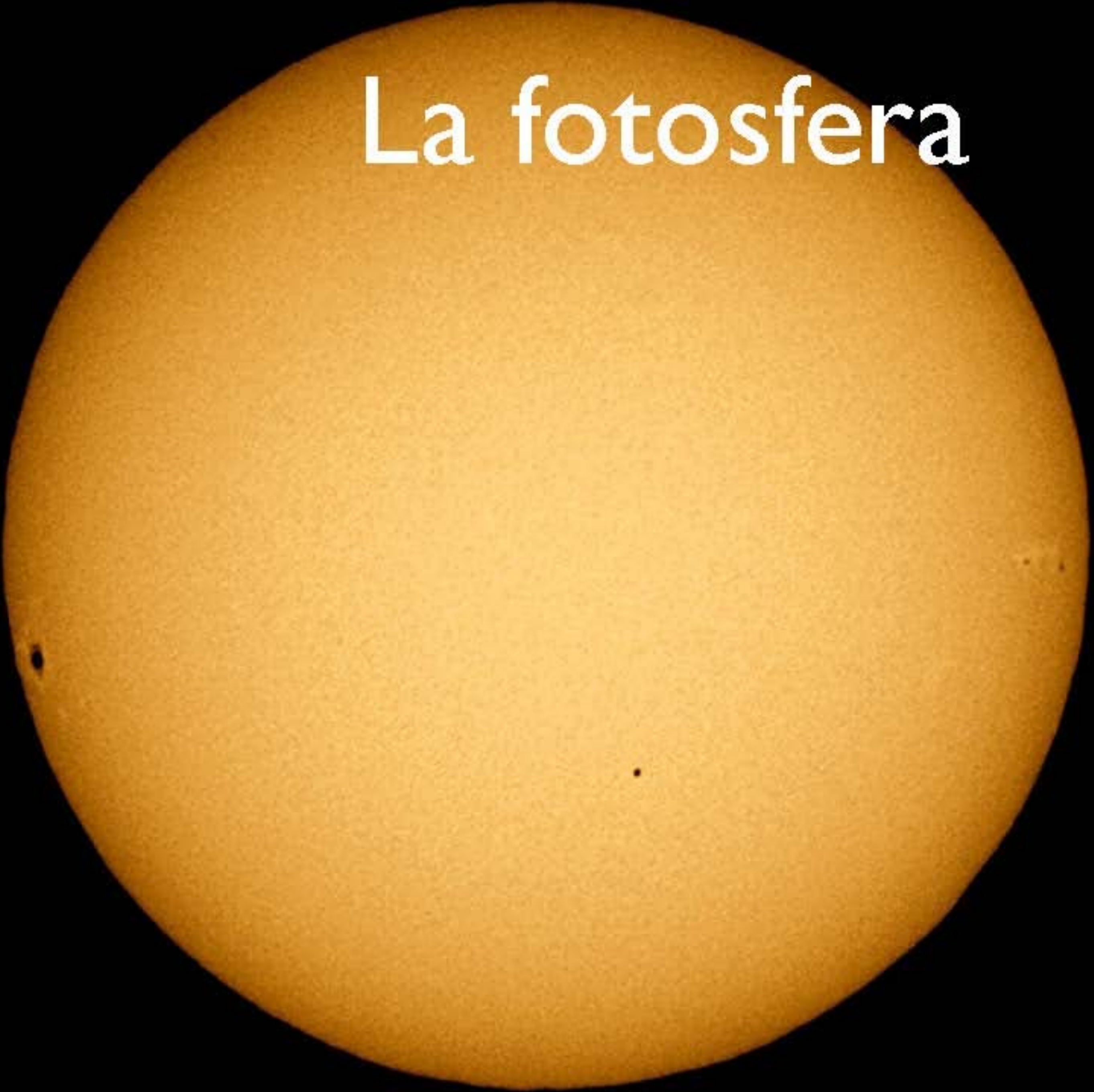
- Su un metro quadro sulla Terra “piovono” 1360 Watt
- Dalla distanza Sole-Terra trovo la luminosità totale: 3.8×10^{26} Watt (!)
- Dalla luminosità calcoliamo la temperatura superficiale di circa 6000 K (radiazione di corpo nero)


Visible, IR and UV radiations
Photosphere 6000 K
Turbulent convection
Coronal hole
100000 K
Convective zone
Radio emission
Core
Radiative zone
Neutrinos
Thermonuclear reactions
Coronal loops
14.000.000 K
Spot
Prominence
Chromospheric flare
Magnetic flux tube
Radio radiations
Energetic particles
Bright spots and short lived magnetic regions
X and γ radiations
X radiations

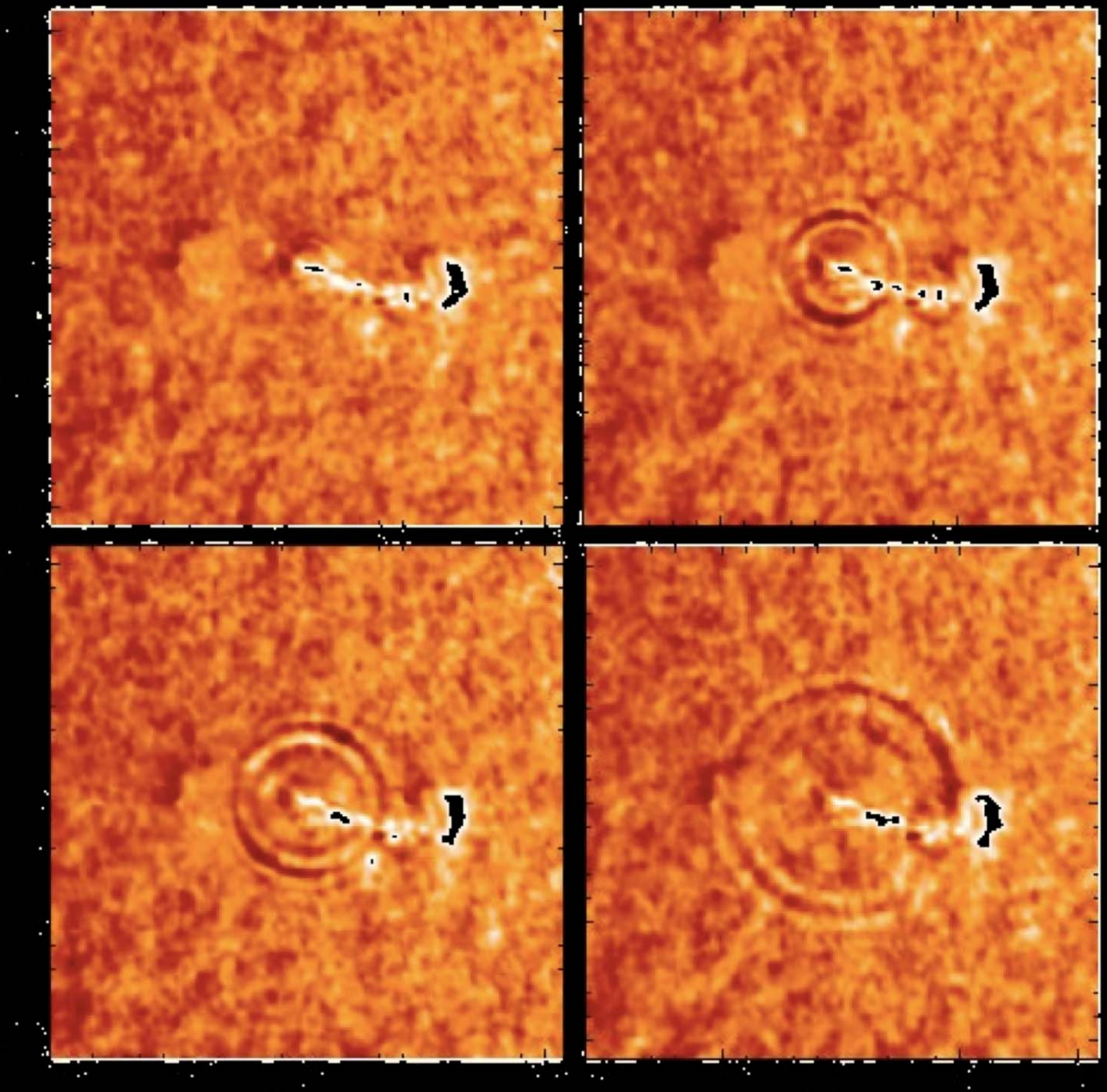
La corona solare

La cromosfera

La fotosfera

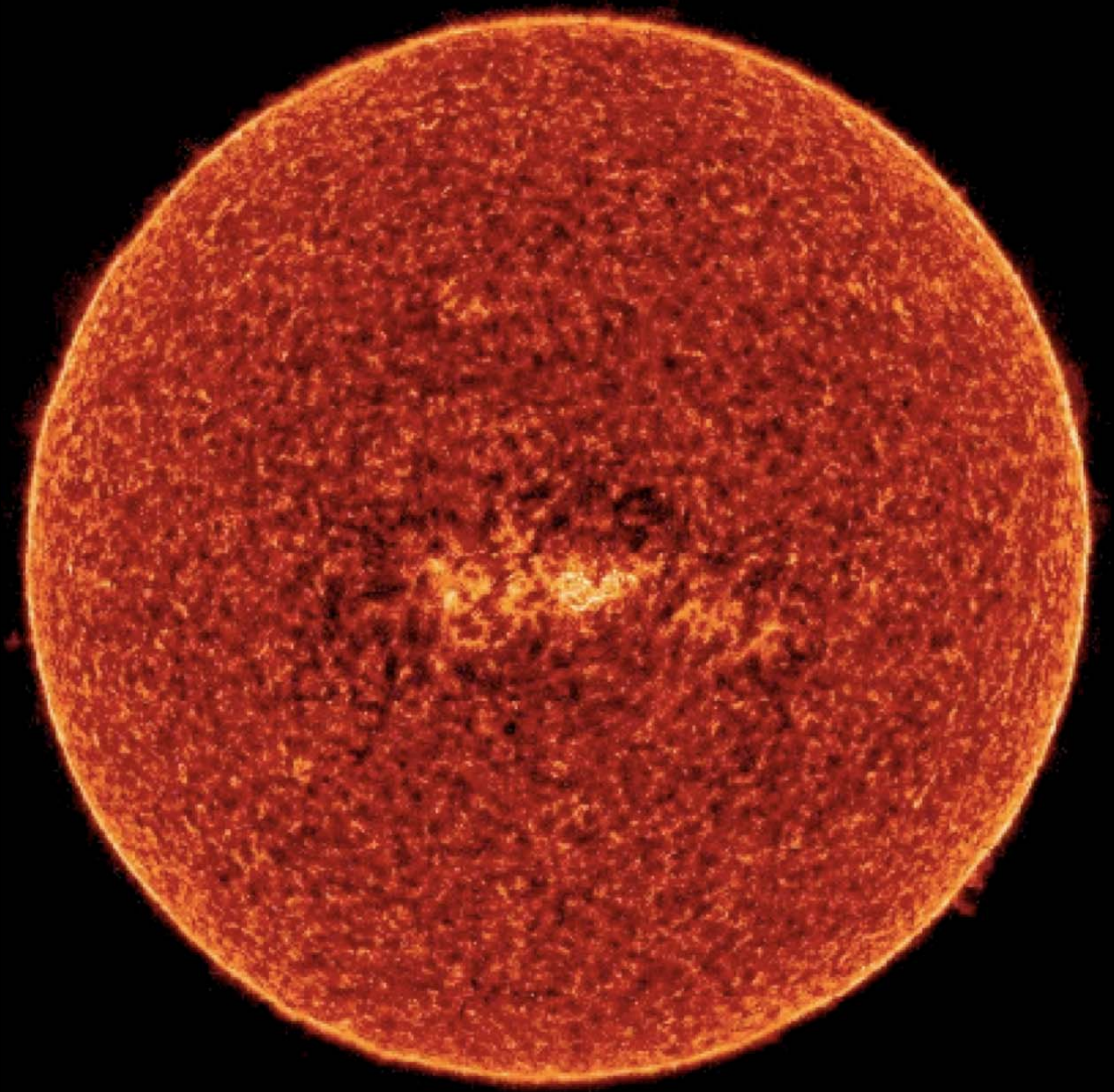


solemoto



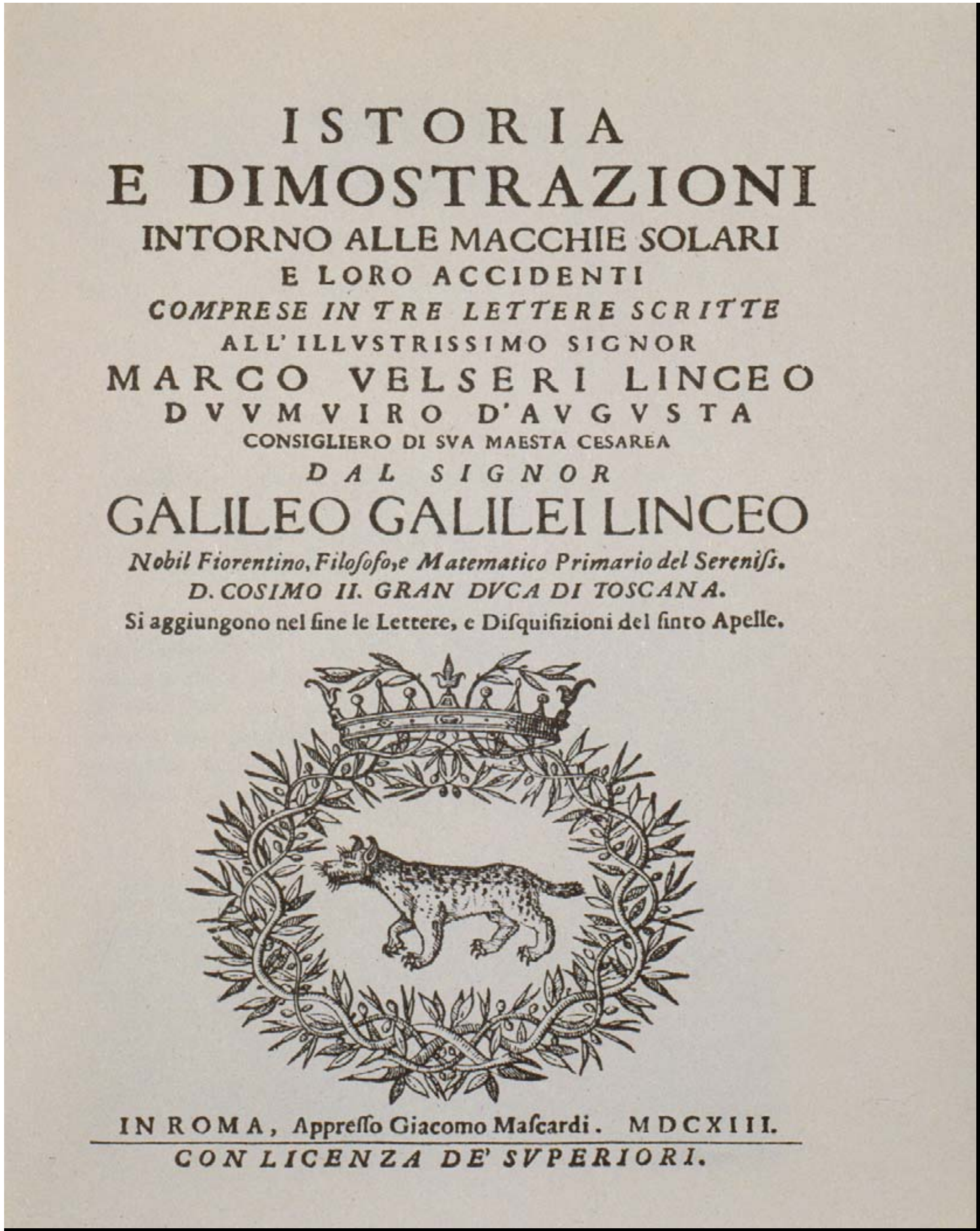
Granulazione

un Sole che bolle



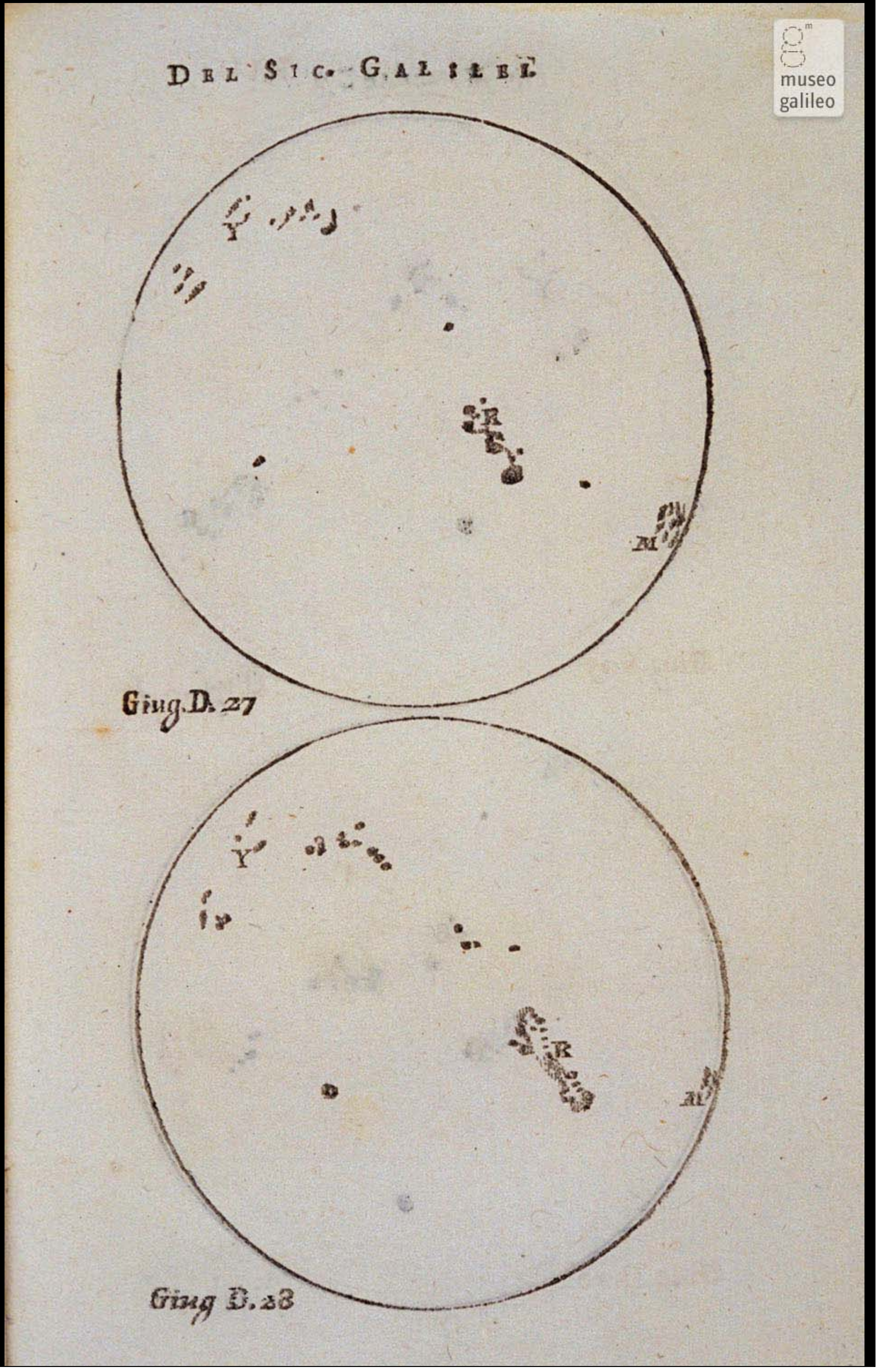
SOHO (NASA/ESA)

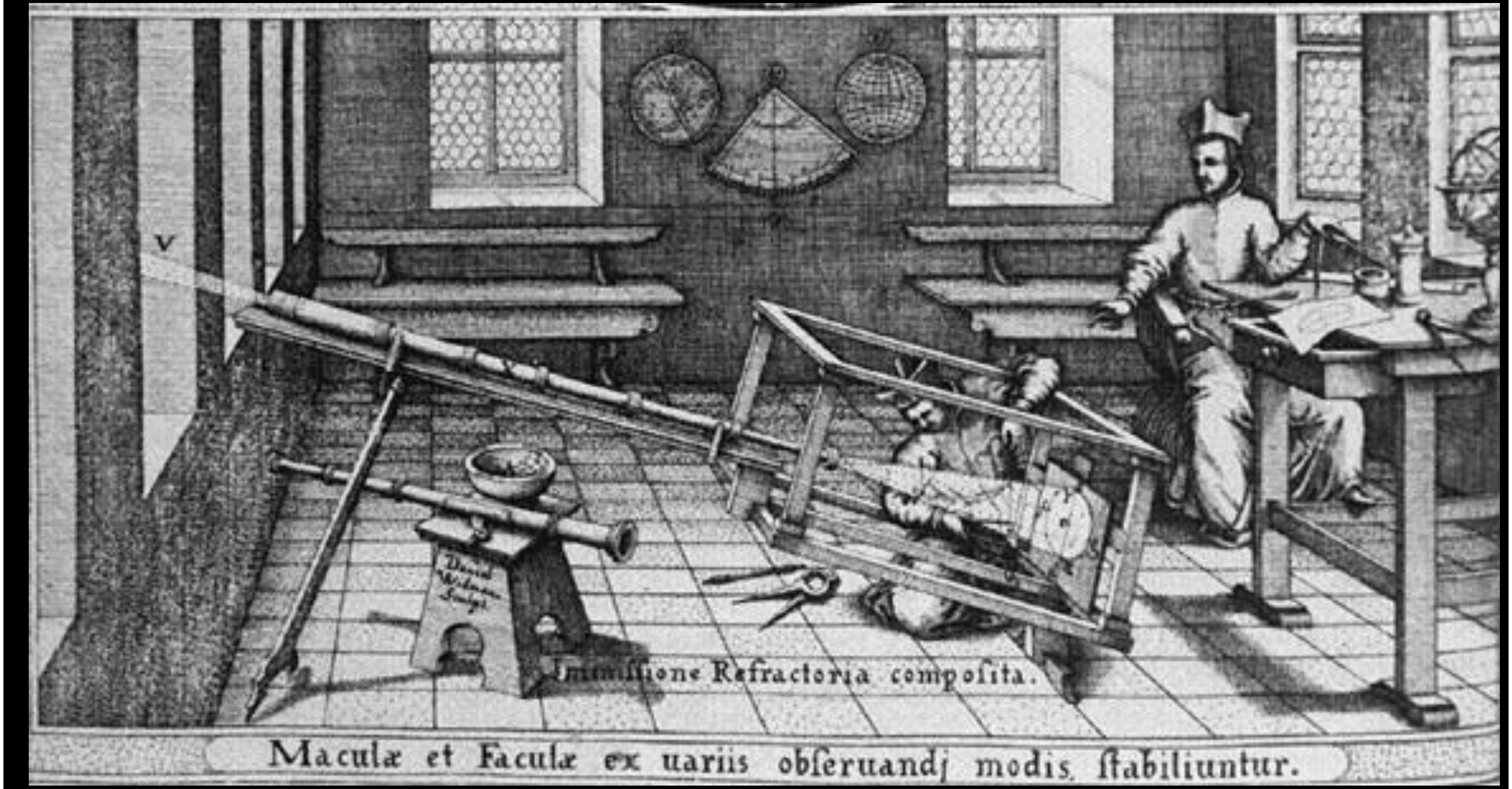
Il Sole osservato nella riga di emissione dello Zolfo a 933 A, alla temperatura di 200000 K



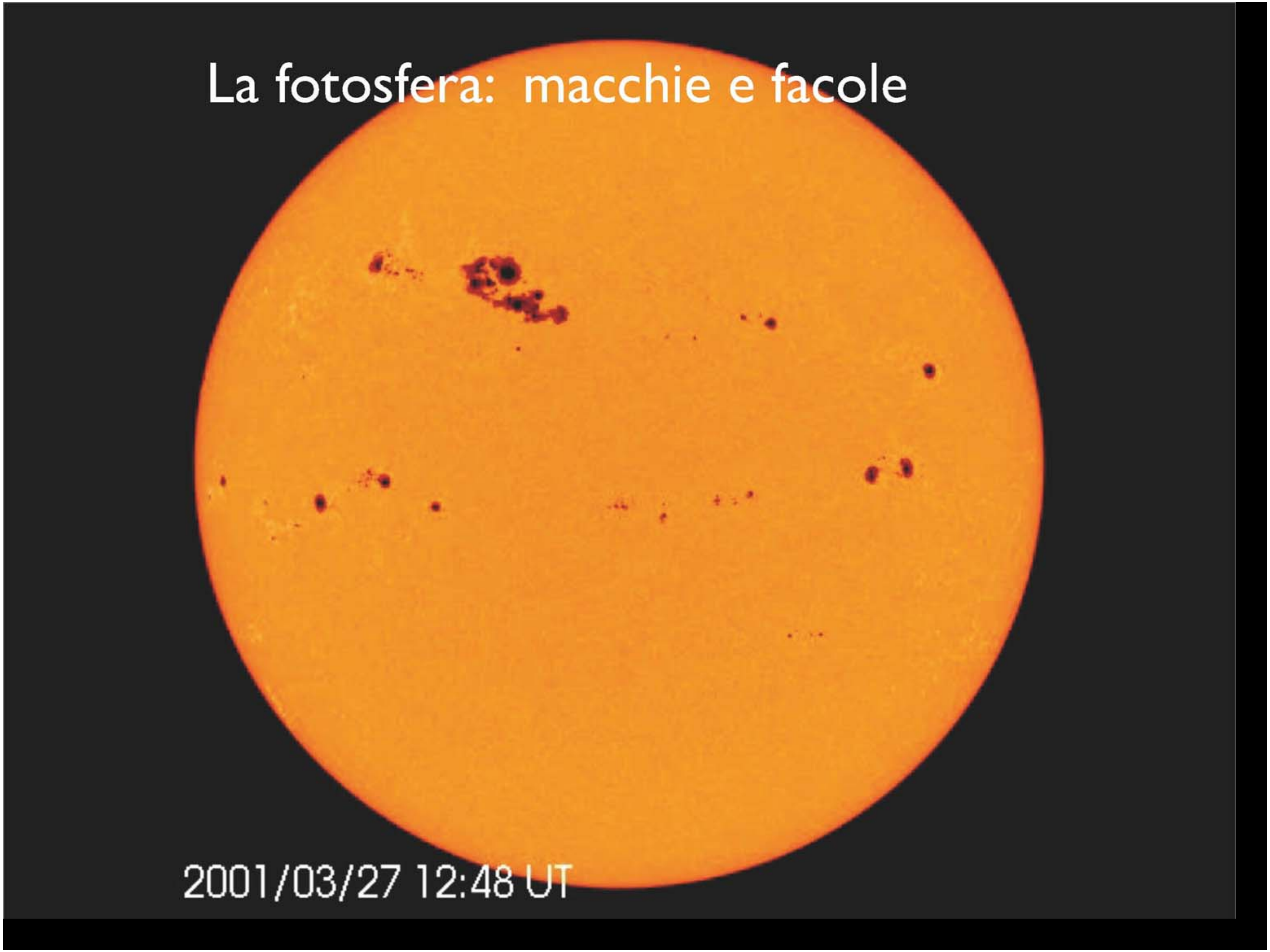
ISTORIA
E DIMOSTRAZIONI
INTORNO ALLE MACCHIE SOLARI
E LORO ACCIDENTI
COMPRESE IN TRE LETTERE SCRITTE
ALL' ILLVSTRISSIMO SIGNOR
MARCO VELSERI LINCEO
DVVMVIRO D'AVGVSTA
CONSIGLIERO DI SVA MAESTA CESAREA
DAL SIGNOR
GALILEO GALILEI LINCEO
Nobil Fiorentino, Filoſofo, e Matematico Primario del Sereniſs.
D. COSIMO II. GRAN DVCA DI TOSCANA.
Si aggiungono nel fine le Lettere, e Diſquiſizioni del finto Apelle.

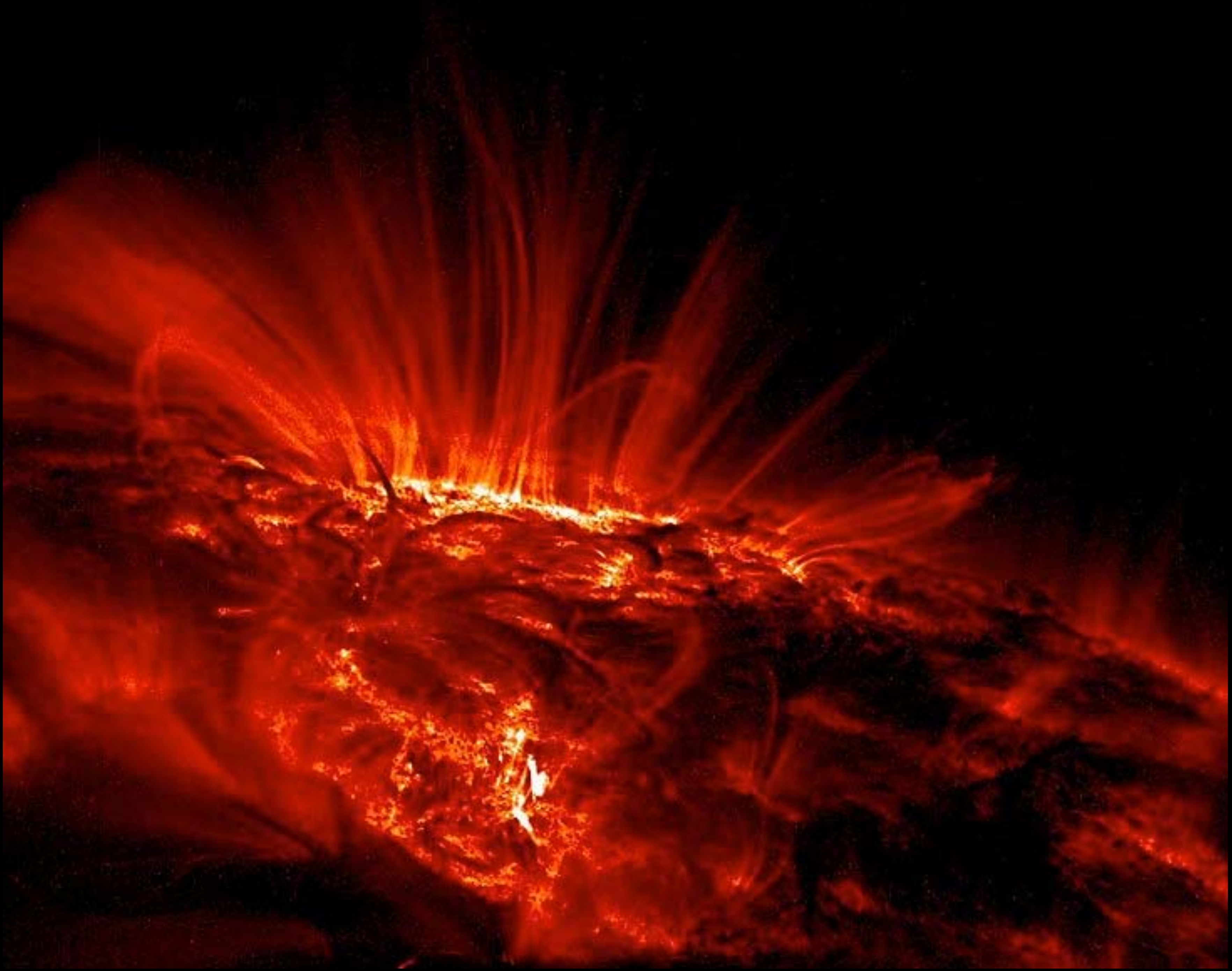
IN ROMA, Appreſſo Giacomo Maſcardi. MDCXIII.
CON LICENZA DE' SVPERIORI.

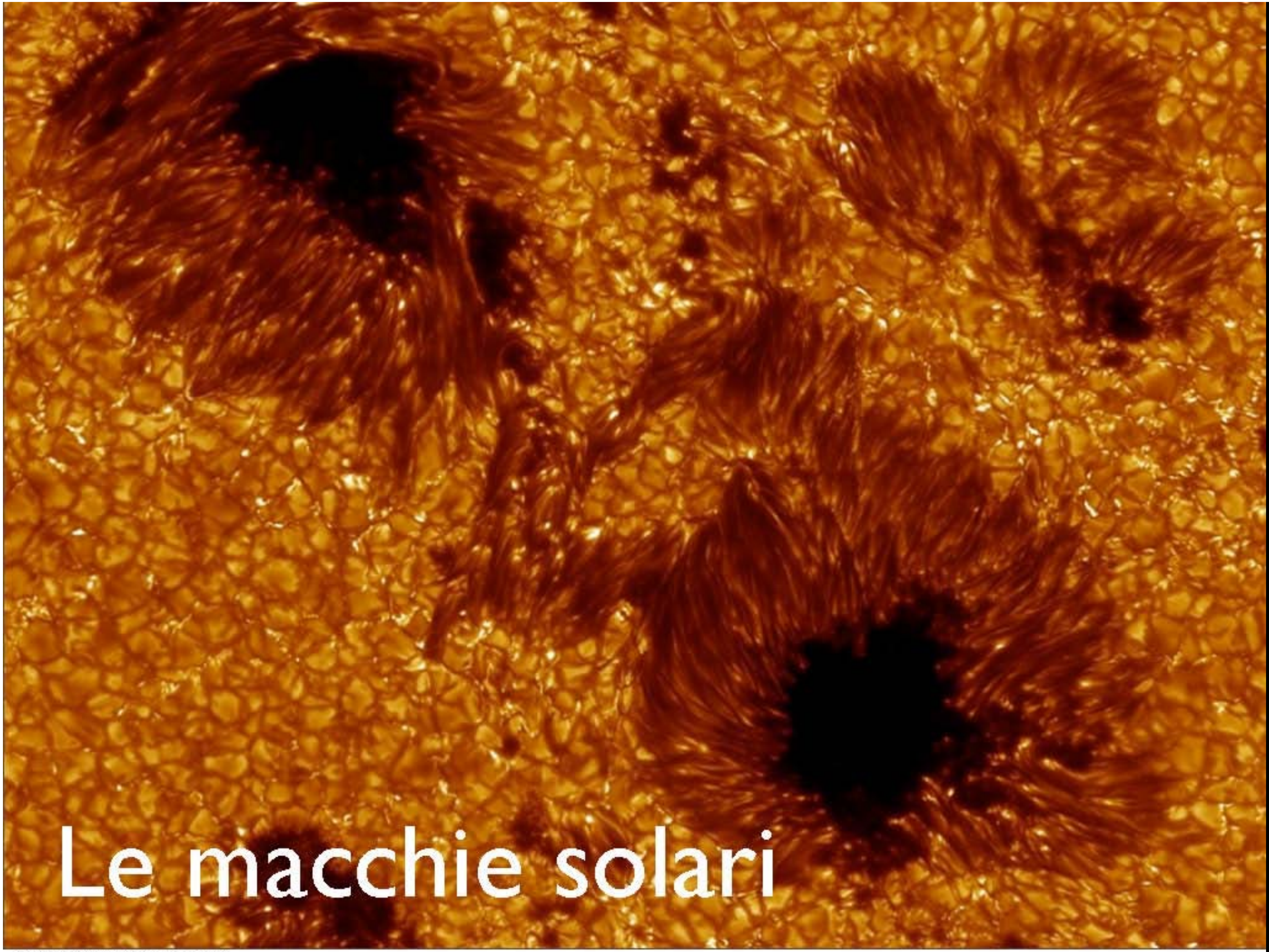



V
David Widman Sculpſit
Immiſſione Refractoria compoſita.
Maculæ et Faculæ ex uariis obſeruandj modis ſtabiliuntur.

La fotosfera: macchie e facole

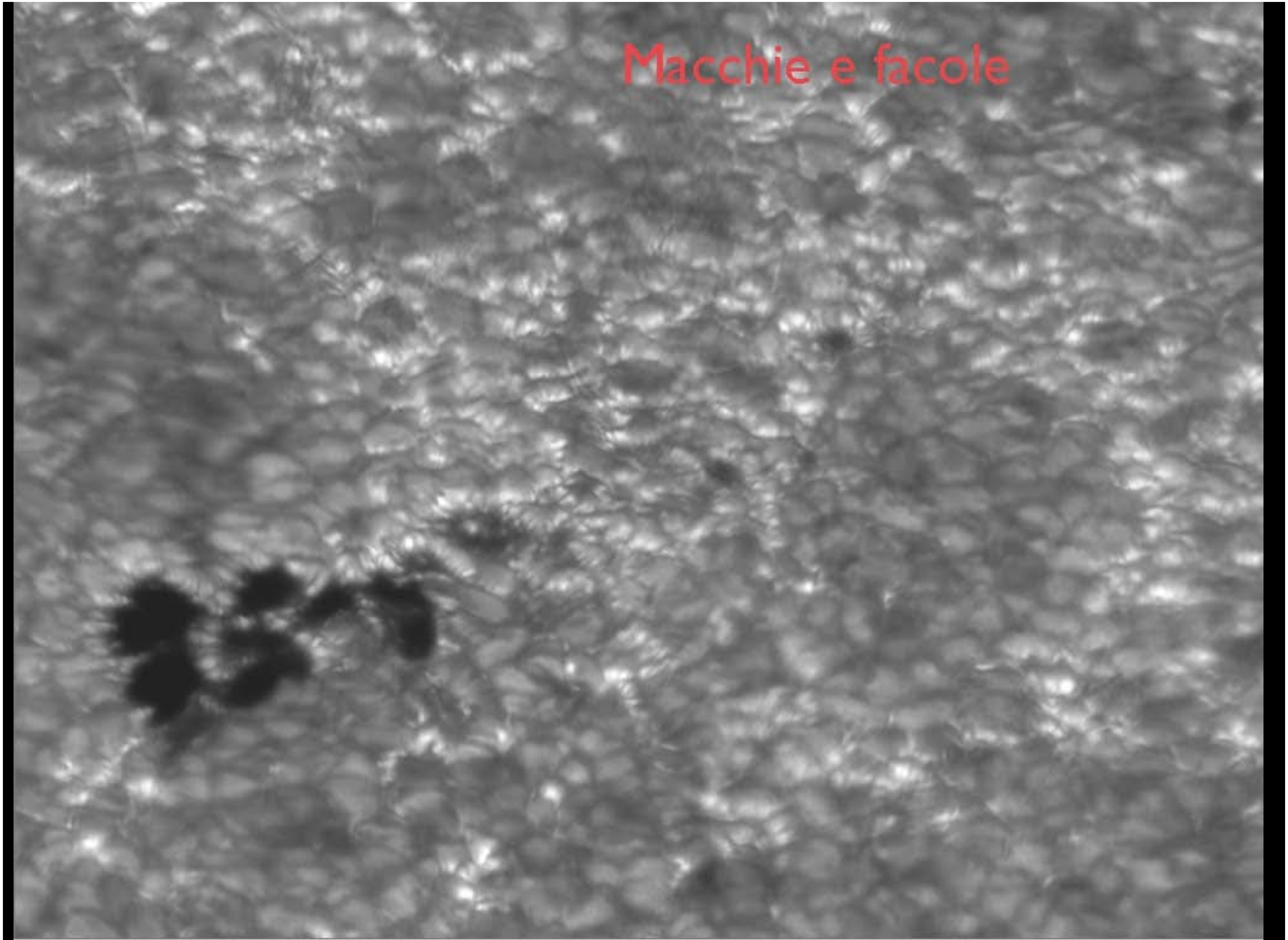


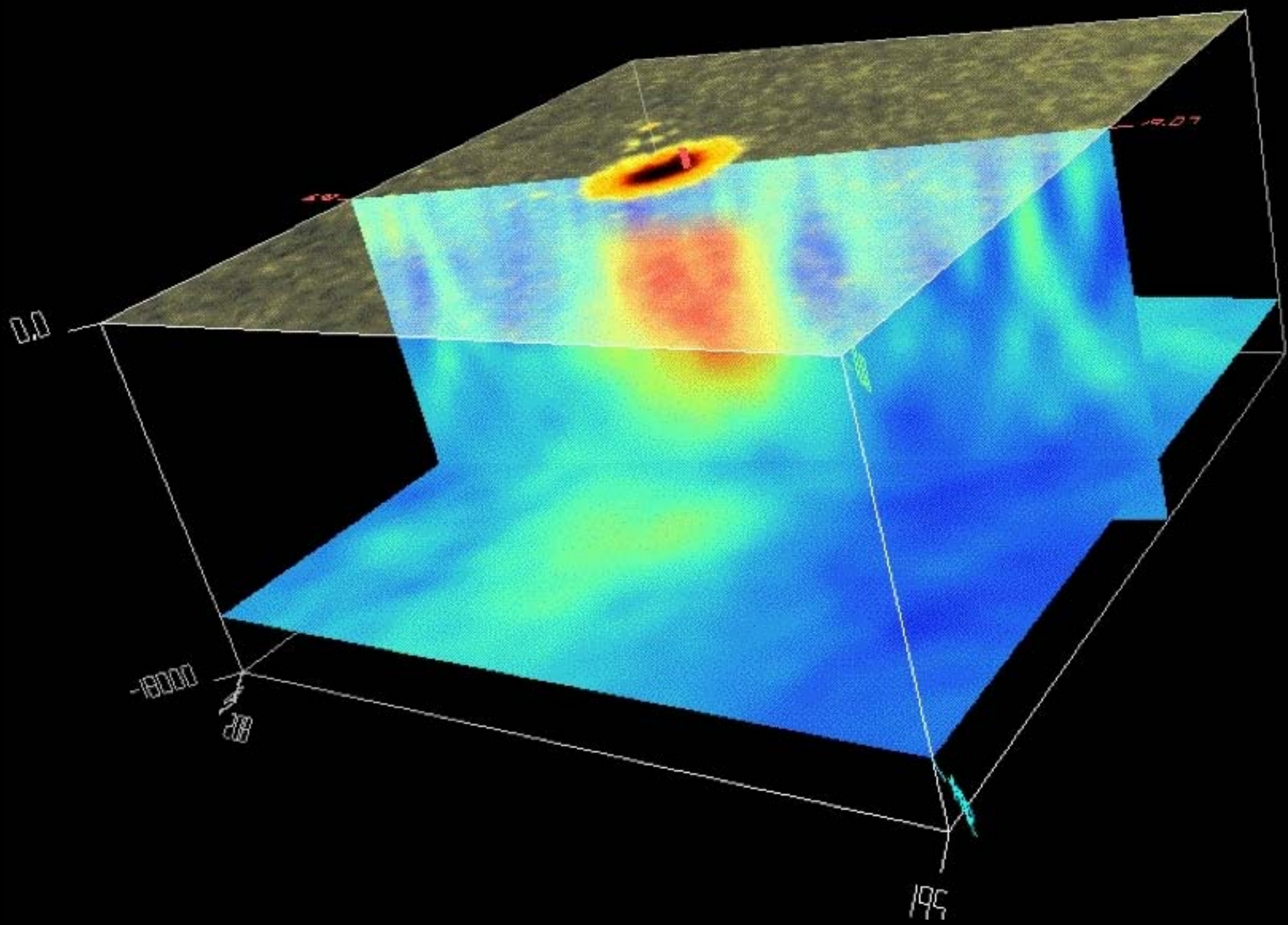


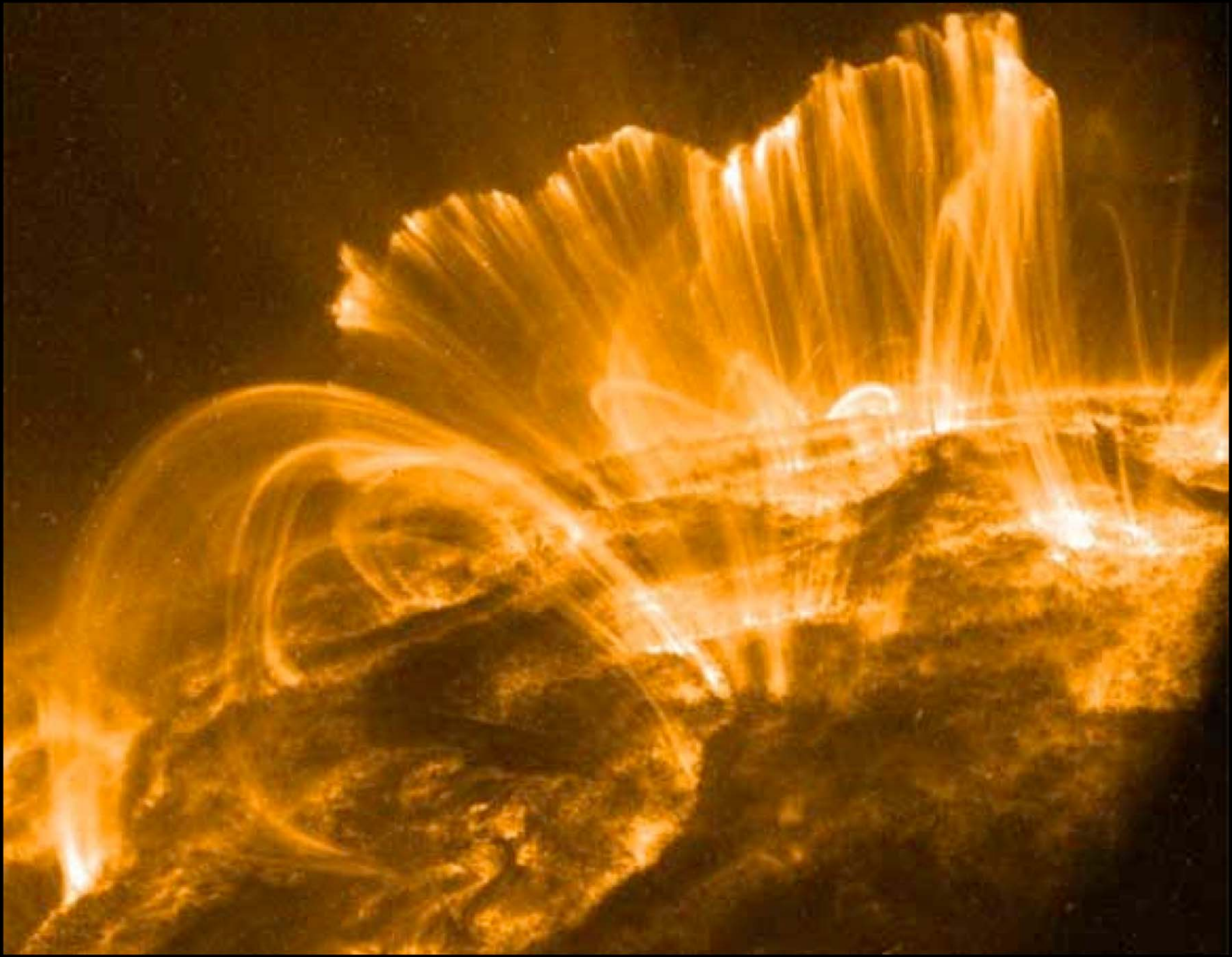


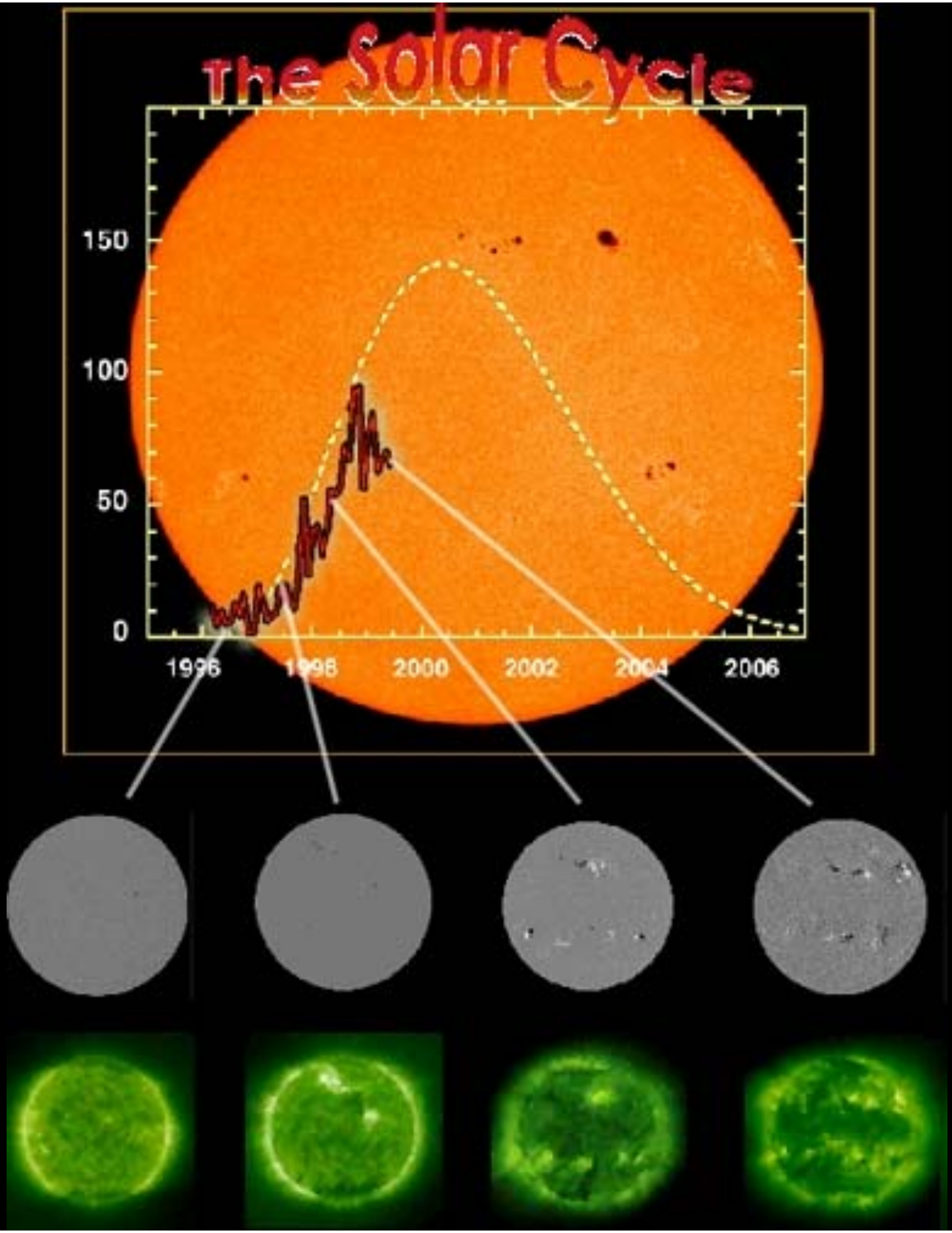
Le macchie solari

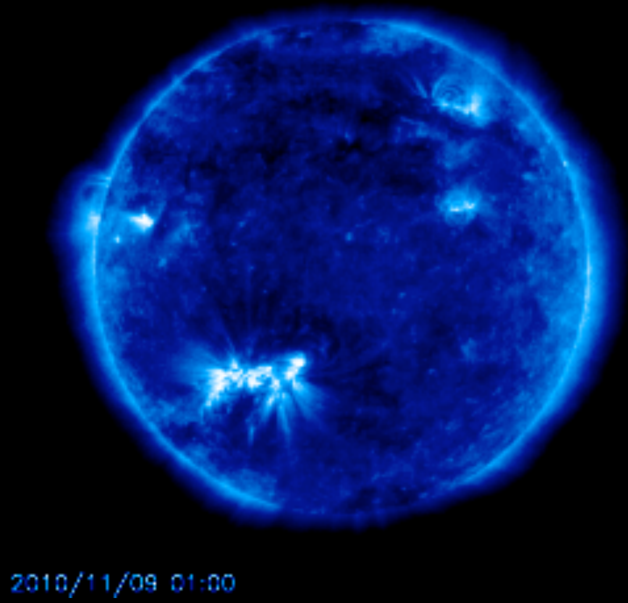
Macchie e facole



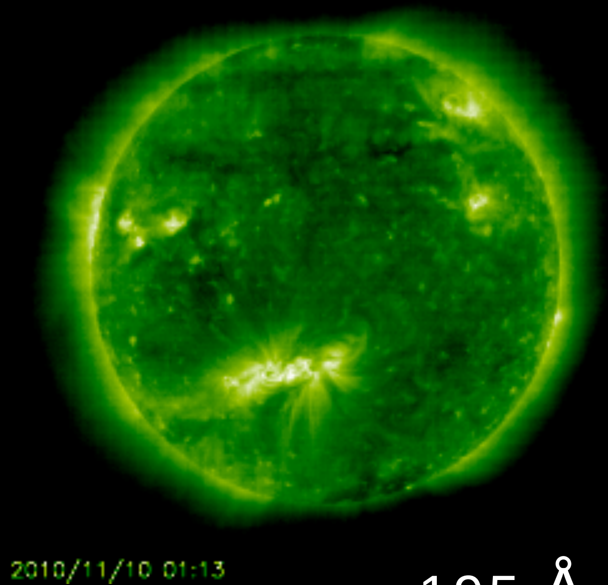

19.07
0.0
-18000
28
195



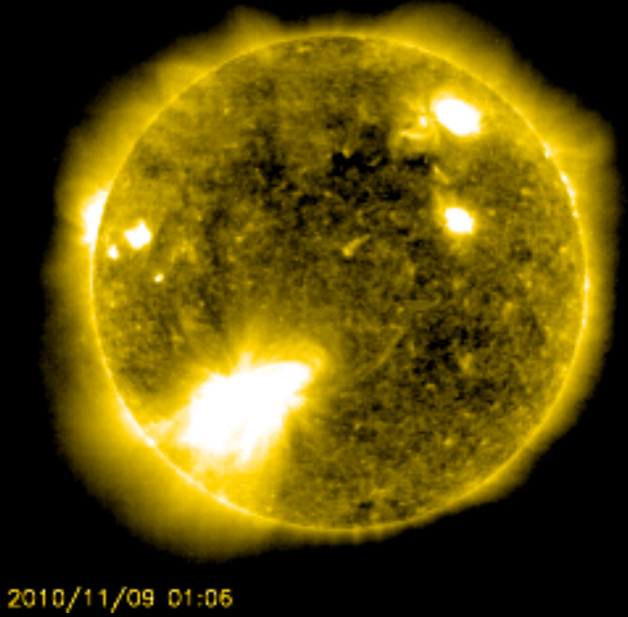

The Solar Cycle
150
100
50
0
1996
1998
2000
2002
2004
2006



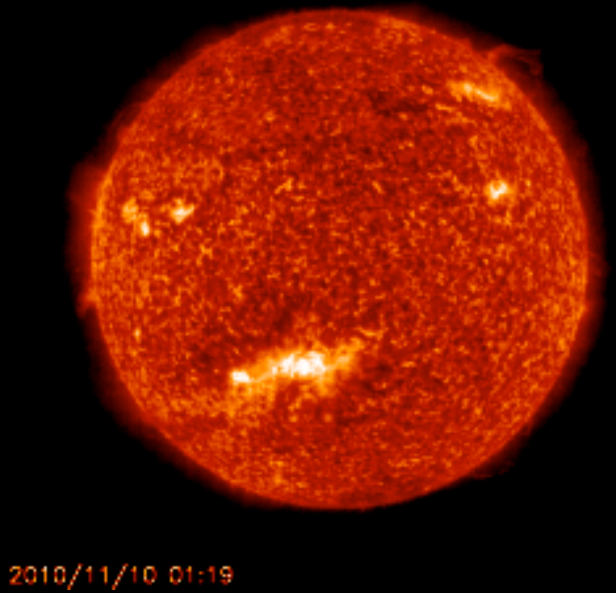
171 Å



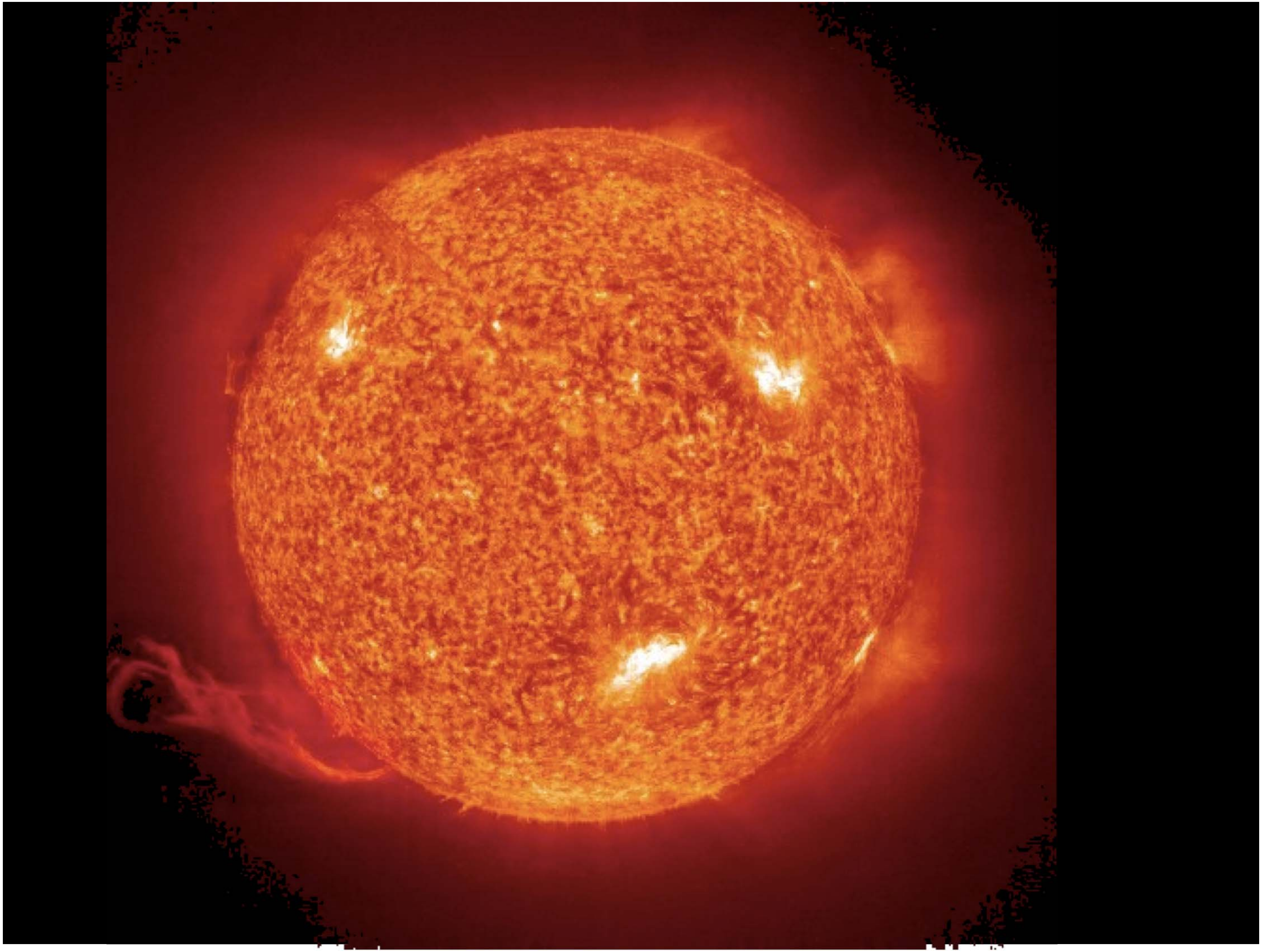
195 Å

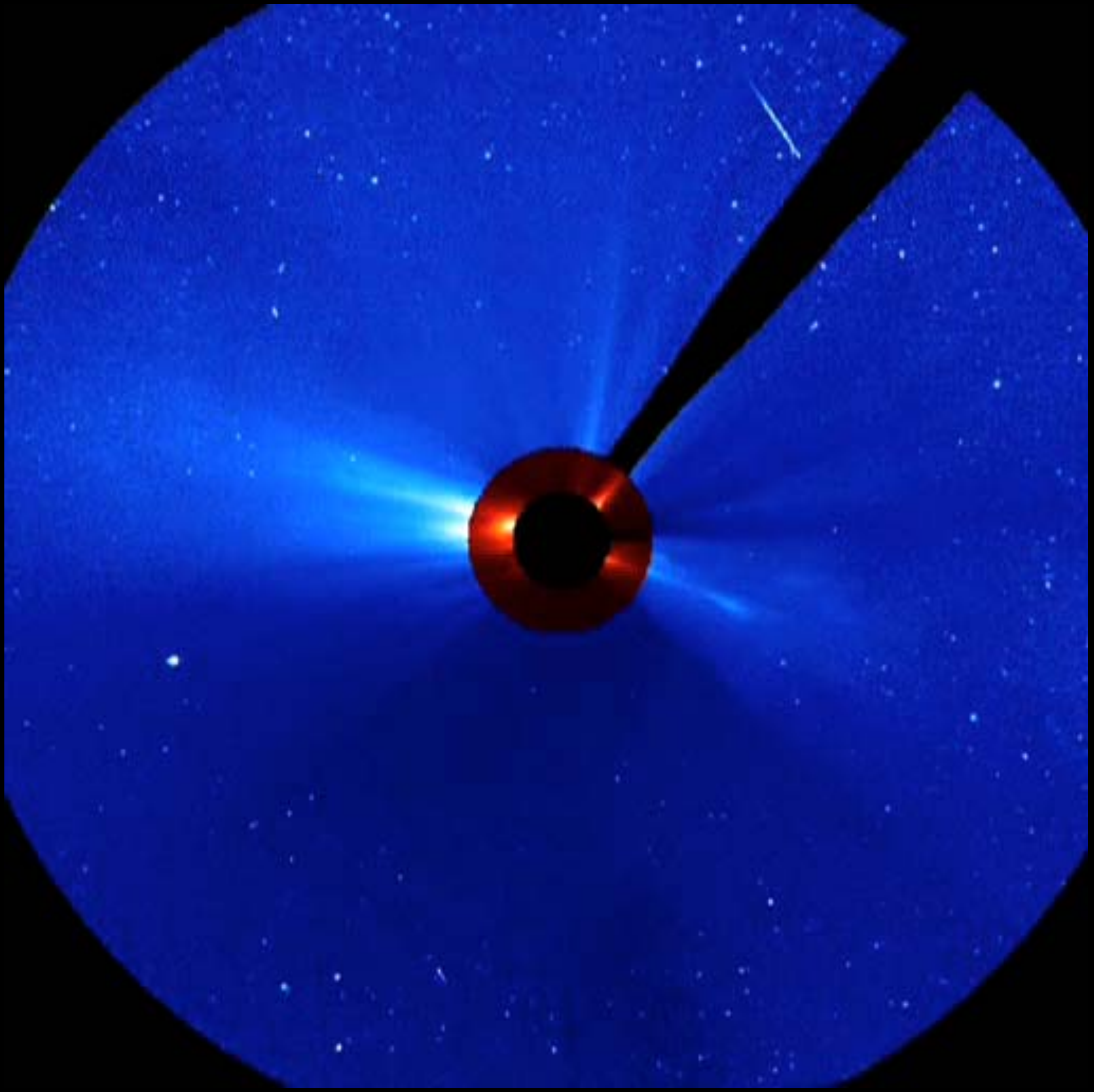


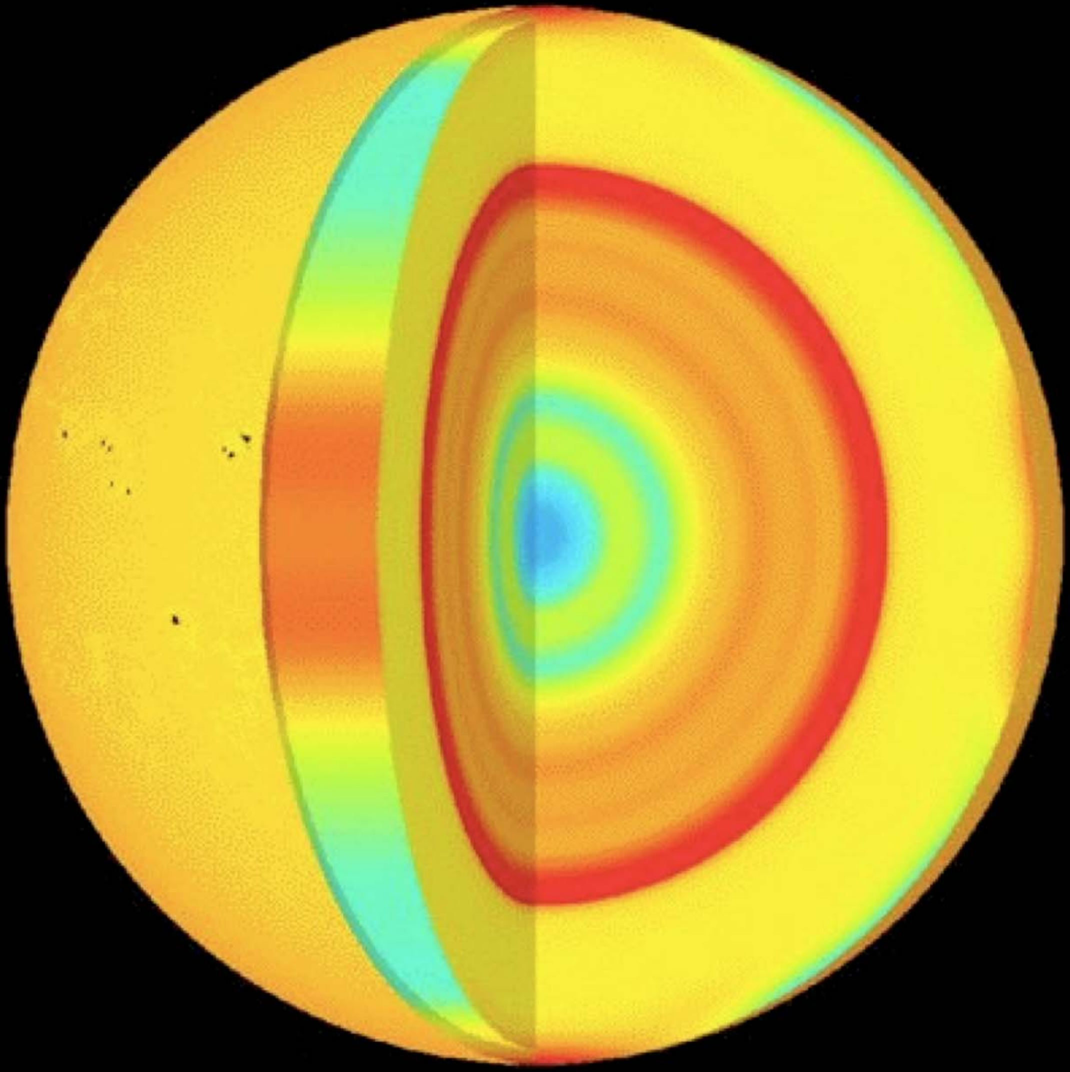
284 Å



304 Å



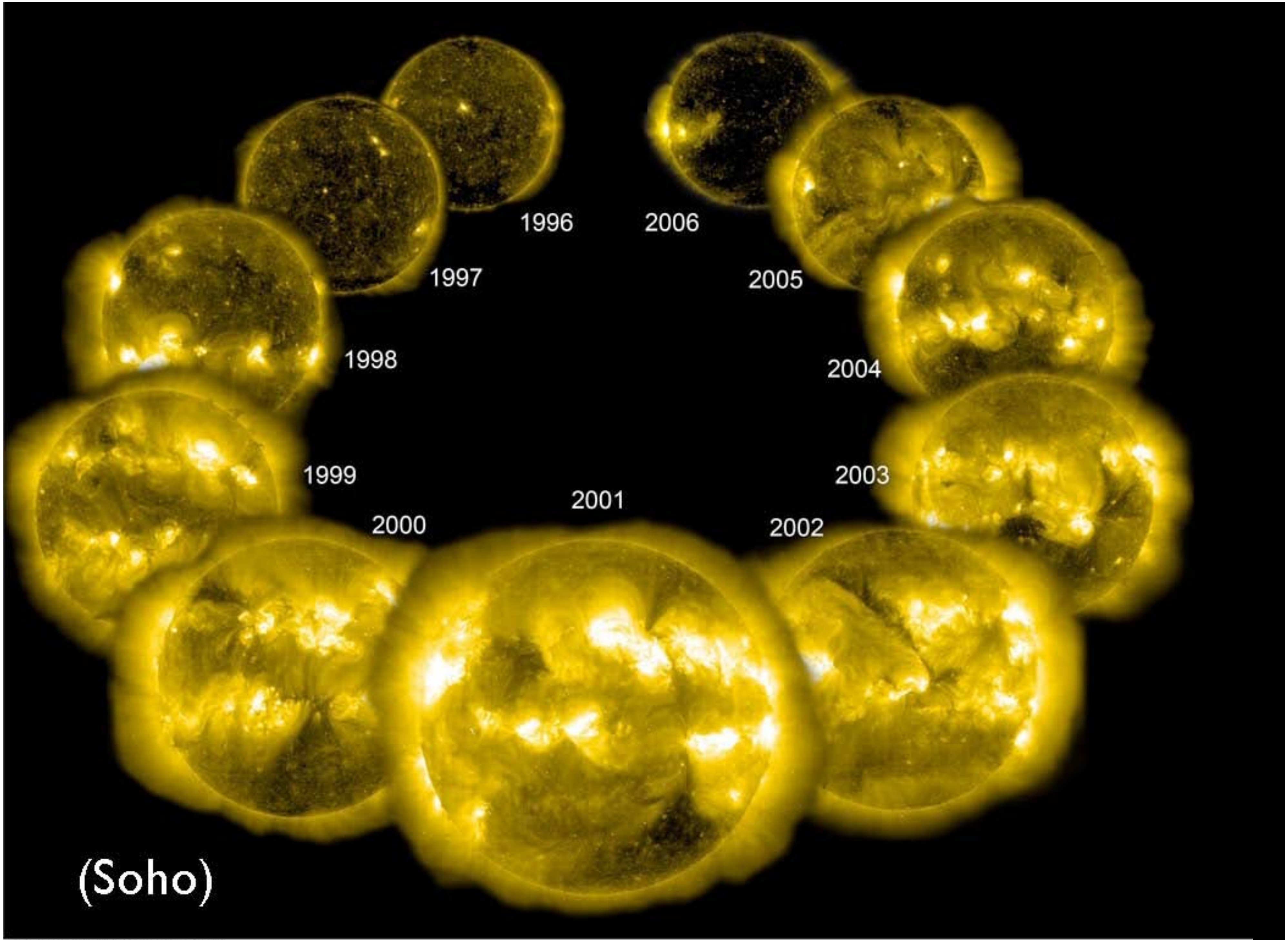




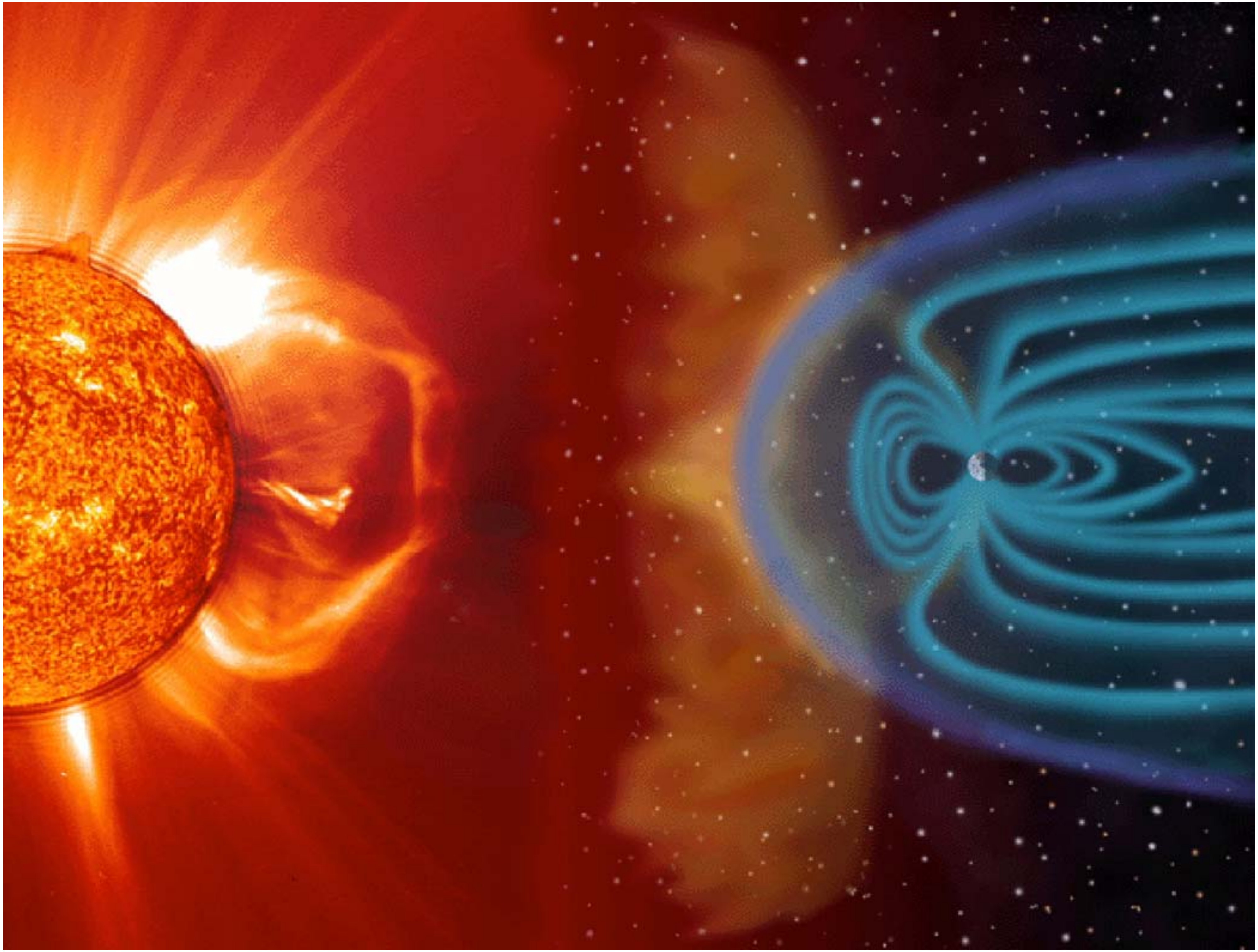
La rotazione all’interno del Sole.

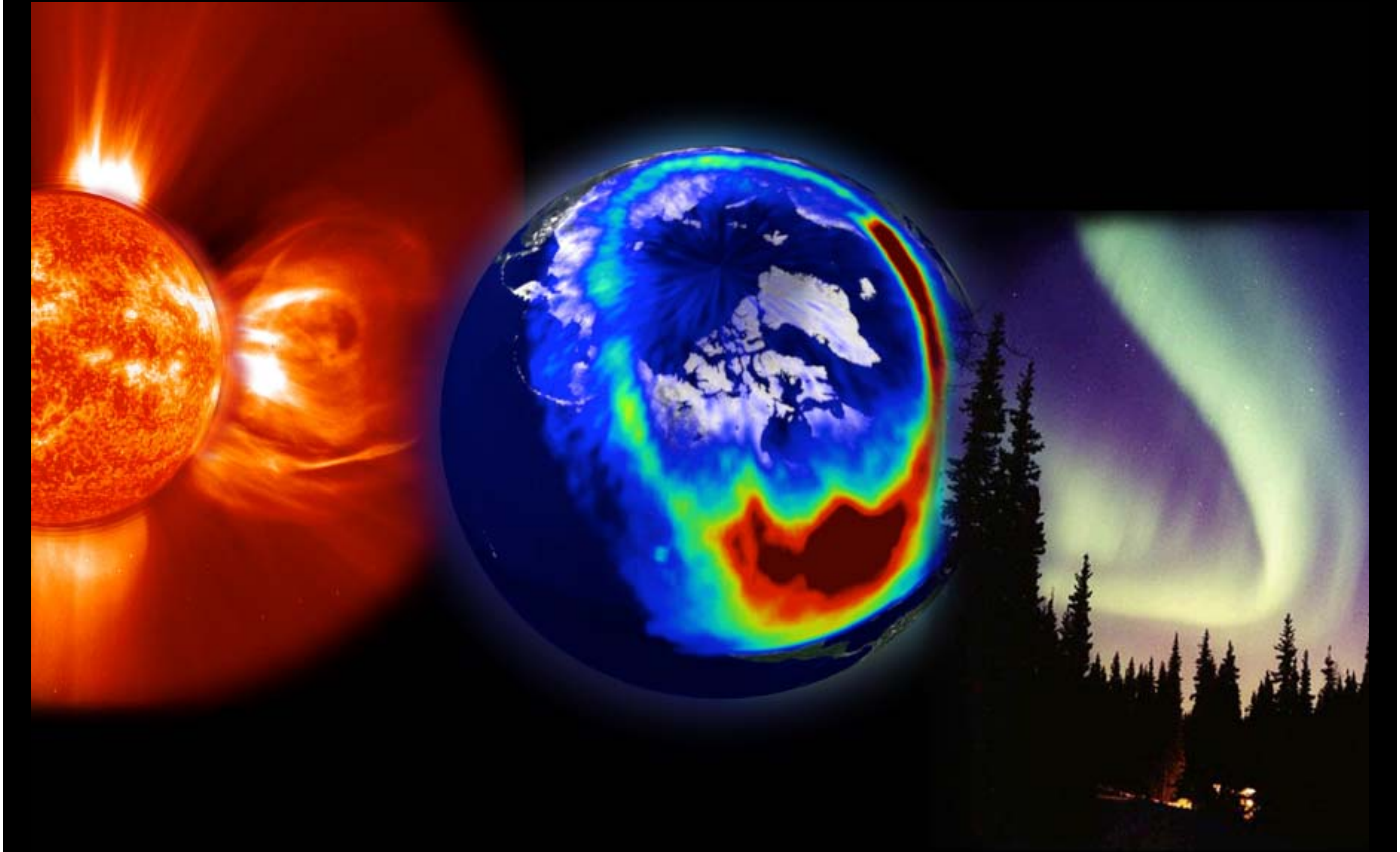
Rosso-Giallo: rotazione veloce
Blu: rotazione lenta.

Le strisce in arancio corrispondono a zone che ruotano
un po’ più velocemente delle loro adiacenze. Penetrano nel sole
per circa 20 000 km



(Soho)

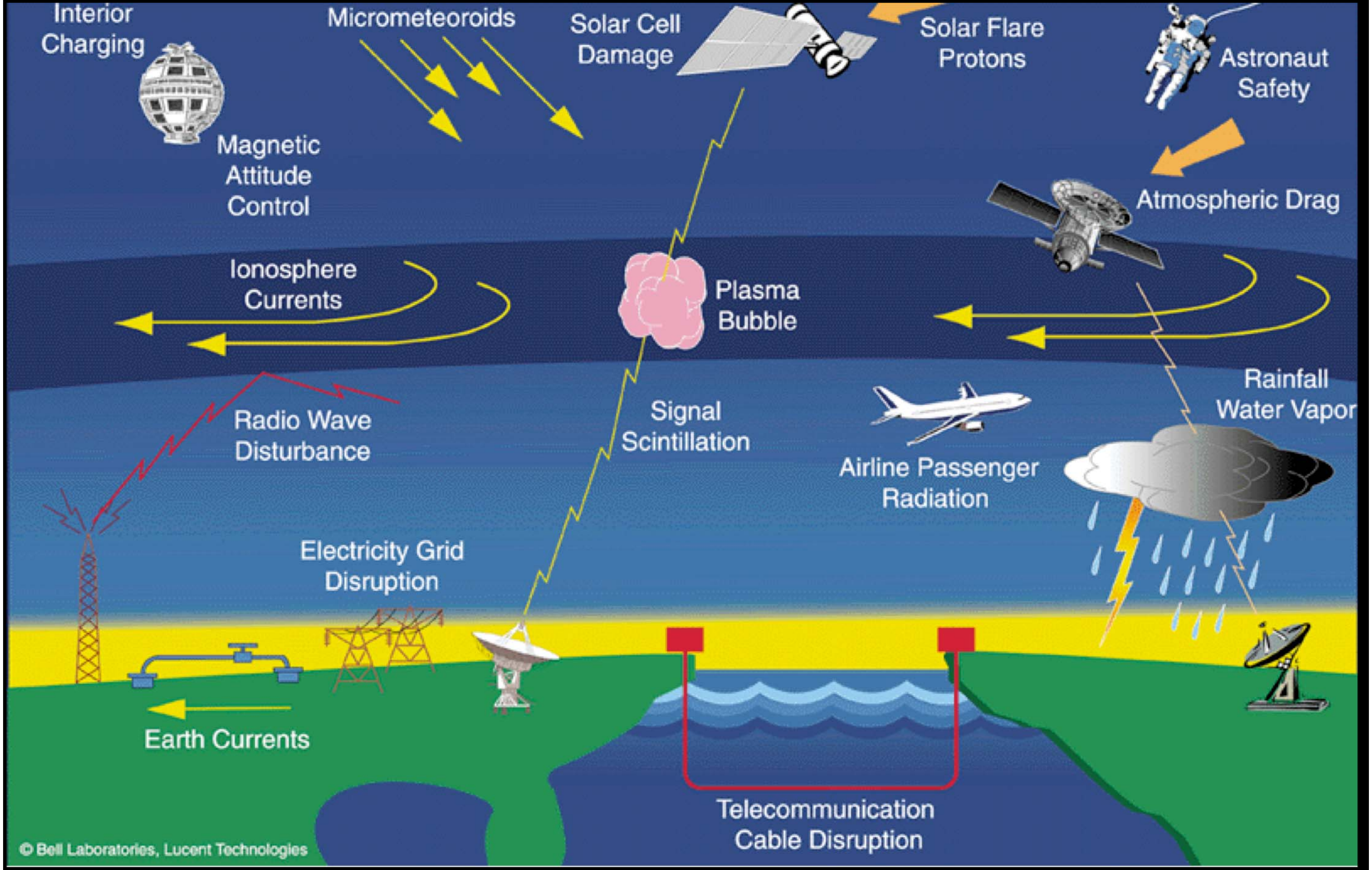




Le aurore polari

Le aurore polari

Quebec, 13 marzo 1989

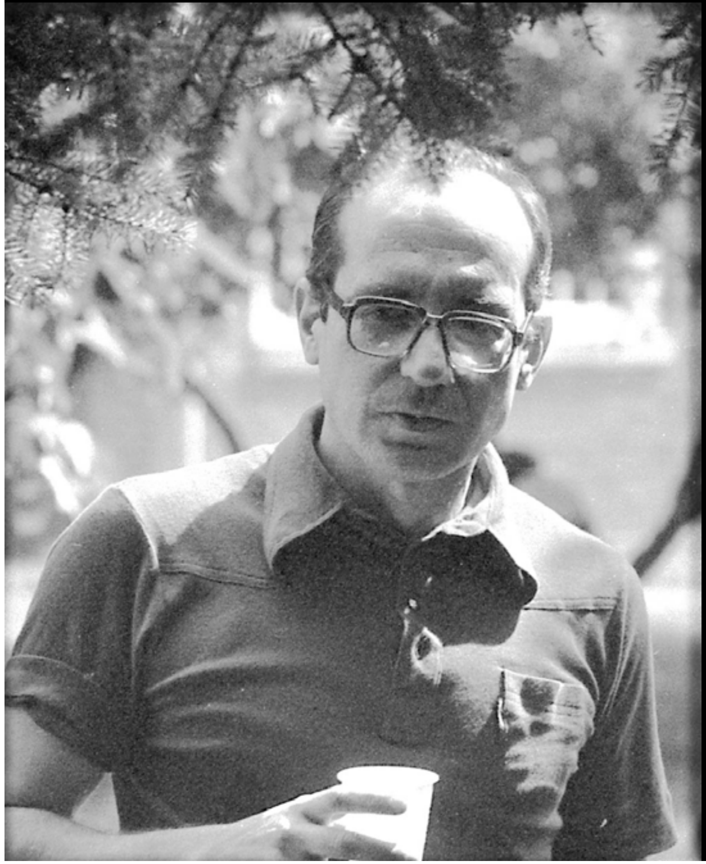


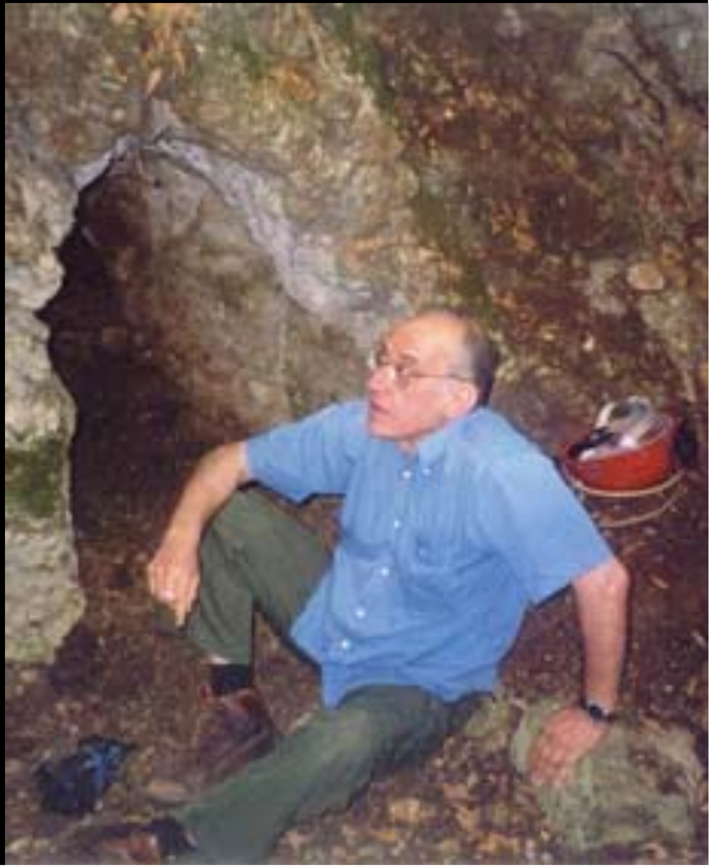
© Bell Laboratories, Lucent Technologies

Fondamenti di Astrofisica Stellare

Vittorio Castellani

http://astrofisica.altervista.org/





Il Sole a occhio nudo

È luminoso

È colorato

È sferico

… l’età del Sole

La Terra può essere
più vecchia del Sole?

l'età del Sole

1) Il Sole non può essere
più giovane della Terra:

2) L'età della Terra:

4 miliardi di anni

$$T_{sole} \geq T_{terra}$$

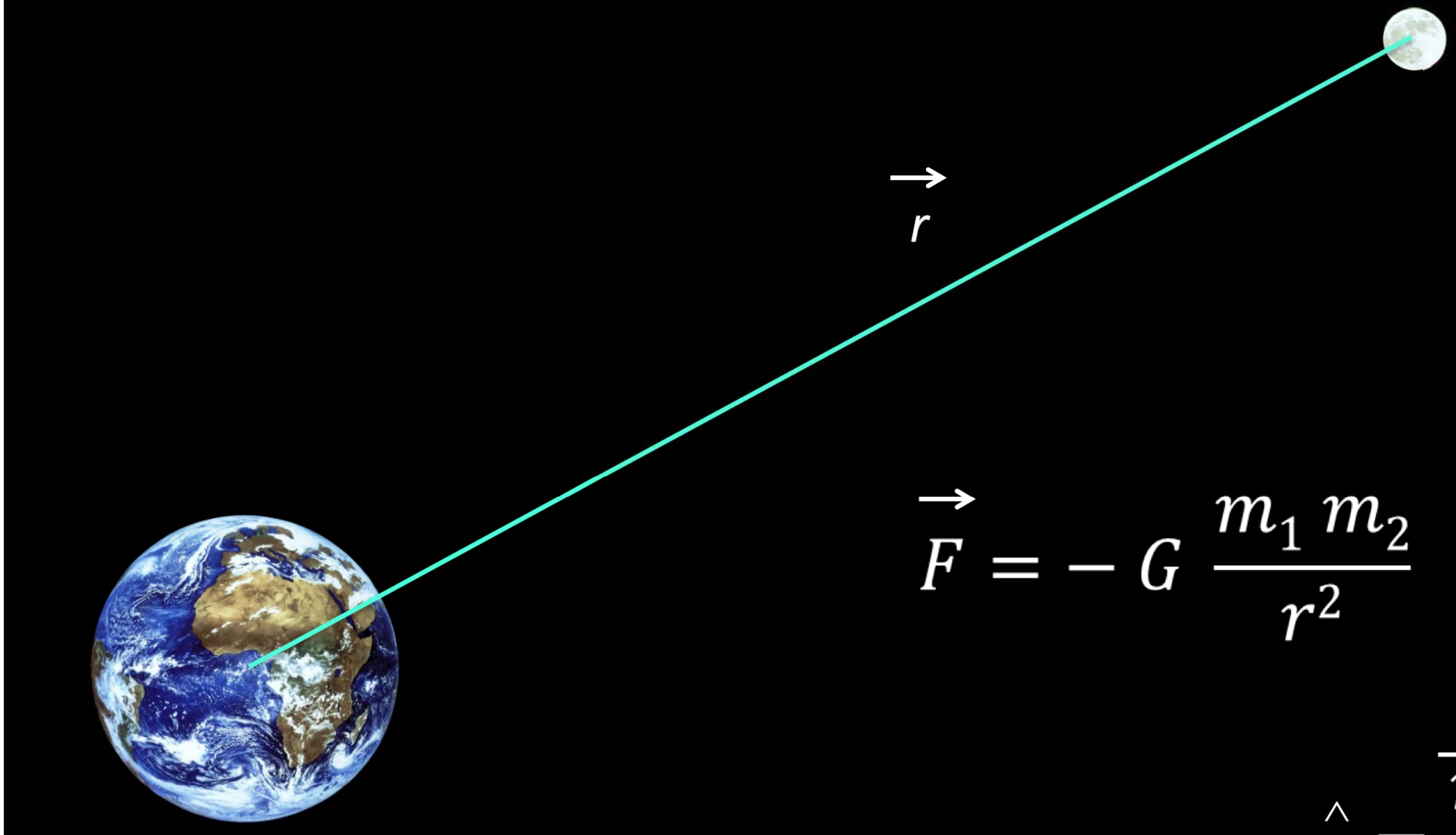
3) 4,5 miliardi di anni

4 miliardi di anni

Meccanica

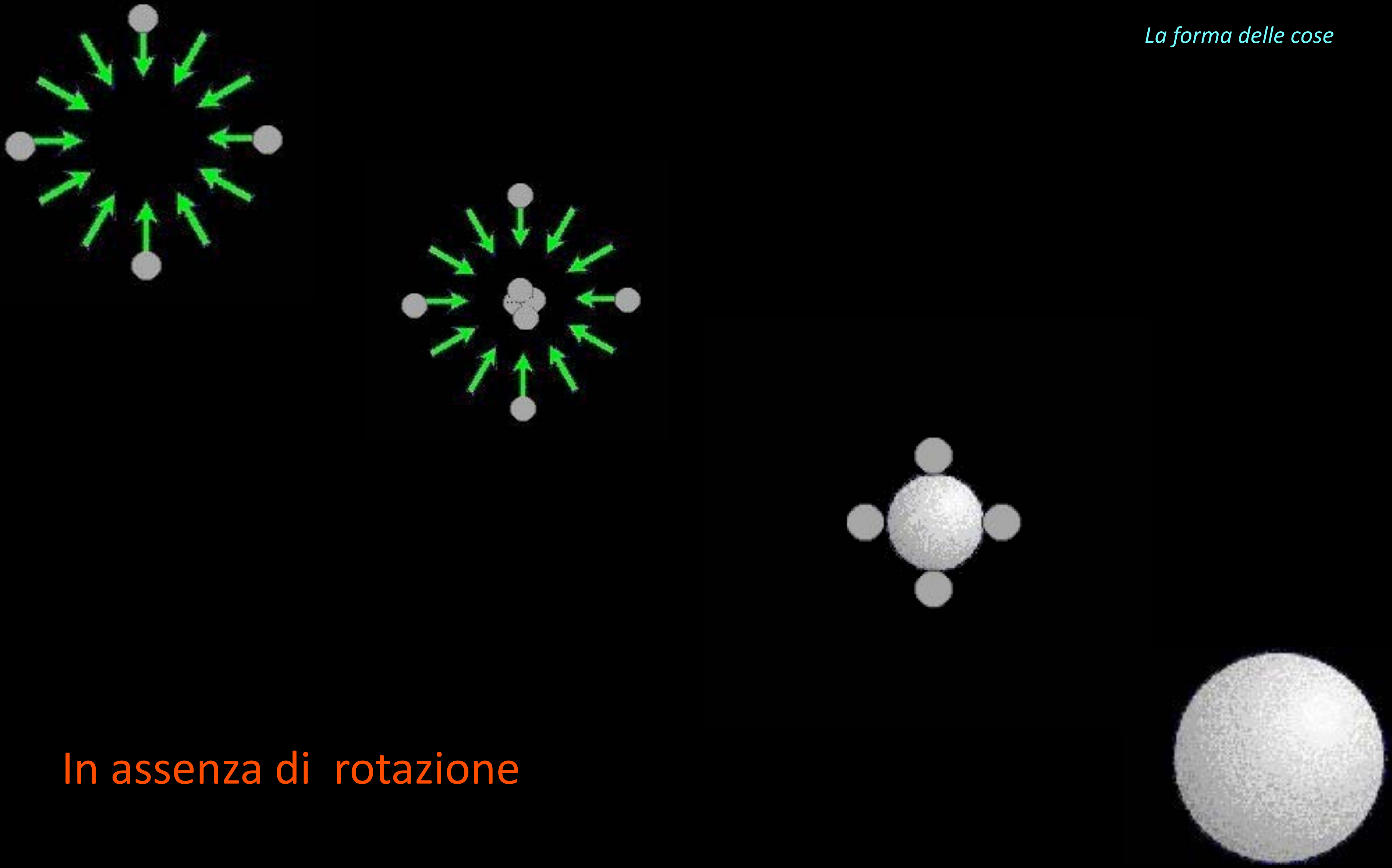
La forma delle cose

La legge di gravitazione



$$\vec{F} = -G\,\frac{m_1\,m_2}{r^2}\;\hat{r}$$

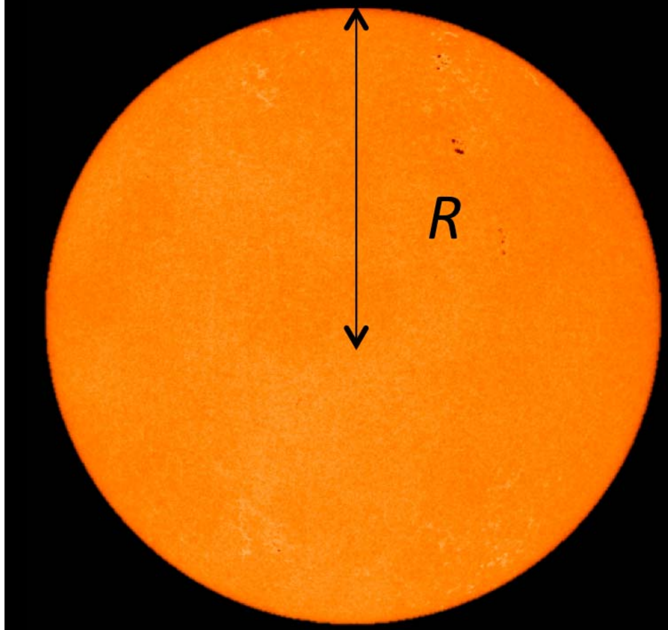
$$\hat{r} = \frac{\vec{r}}{r}$$

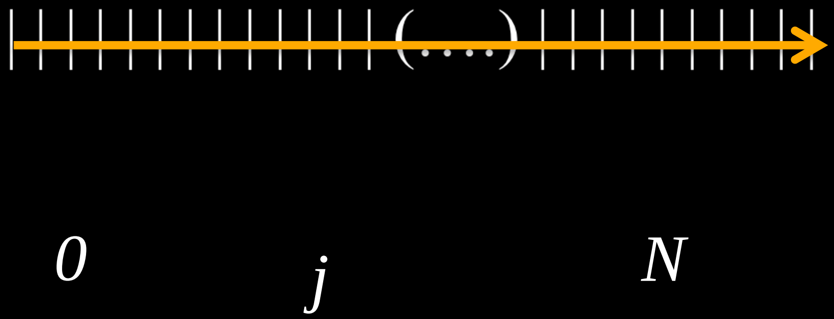


In assenza di rotazione

una forza centrale

costruisce oggetti sferici





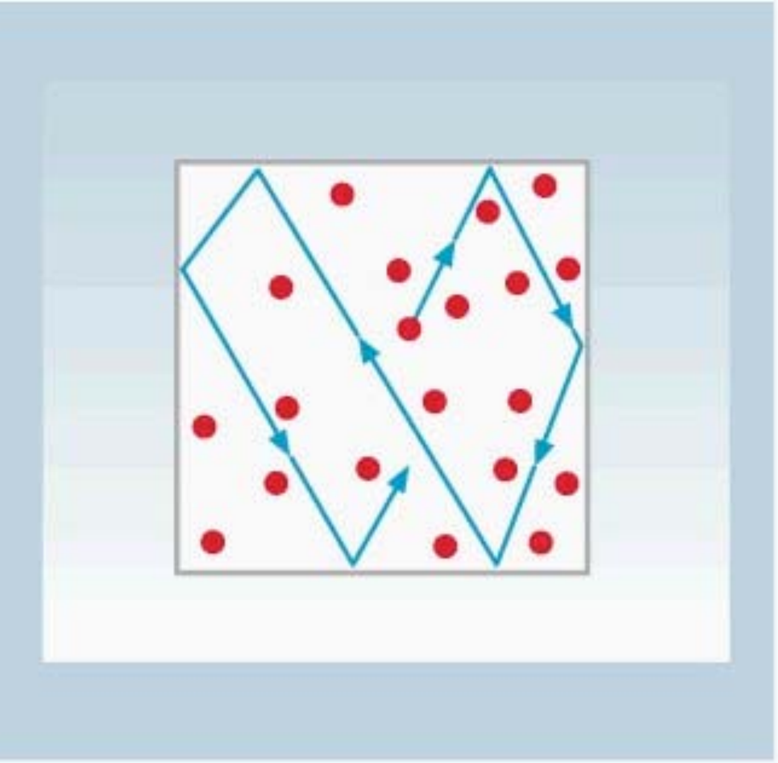
$j = 0, N$


(....)
0
j
N
j = 0, N

Termodinamica

Il sole è una sfera di gas

gas perfetto

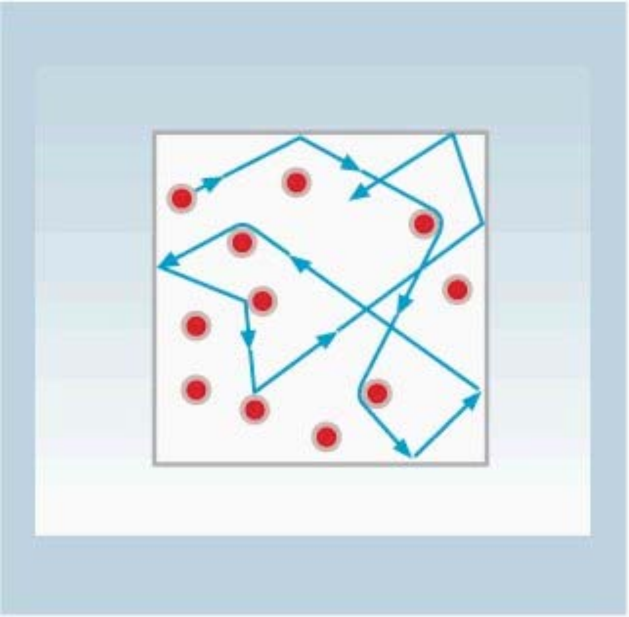


equazione di stato

$$PV = nRT$$

Le particelle non si urtano fra loro

gas reale



Le particelle si urtano fra loro:

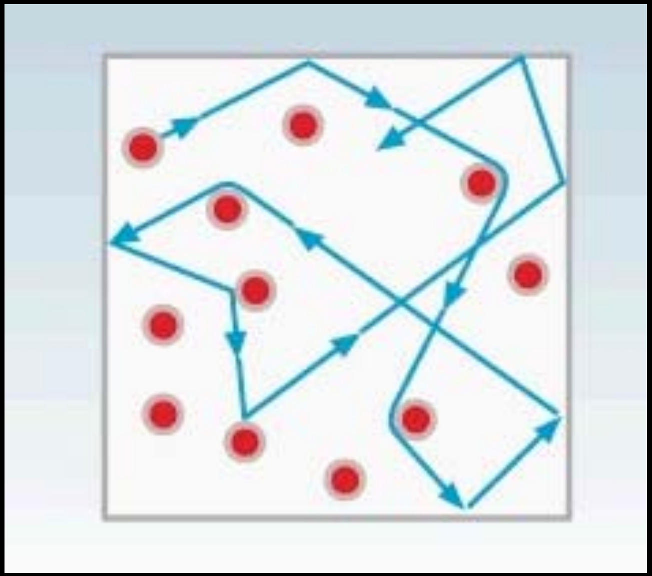
interazione gravitazionale

interazione elettromagnetica

…

Sole: sfera di gas

gas reale



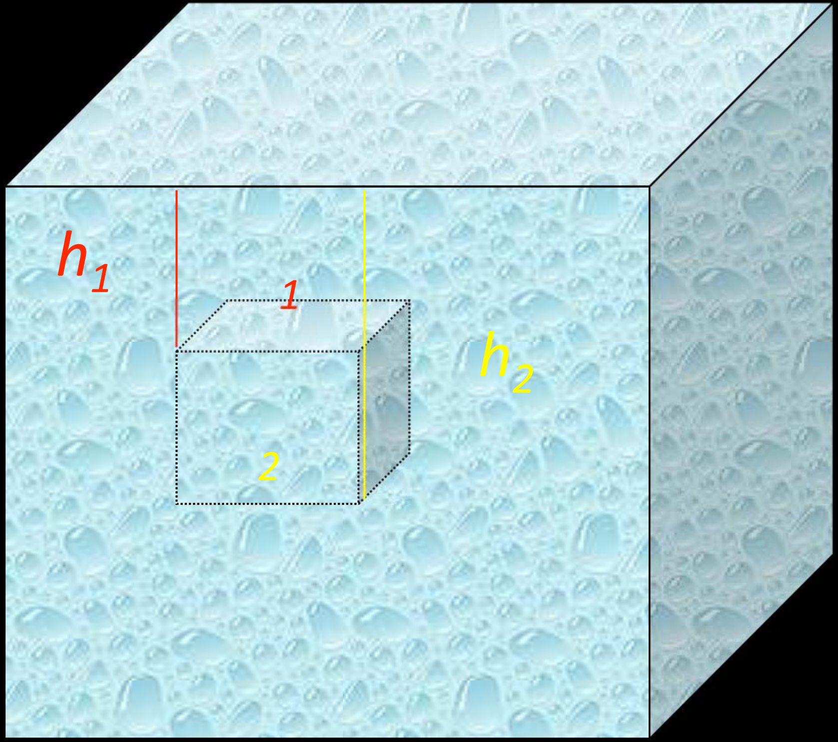
- elettroni
- ioni
- luce

$P = P_{gas} + P_{luce}$

$P_j = P_j\,(\rho_j, T_j)$

equazione di stato

Il sole è in equilibrio (idro)statico

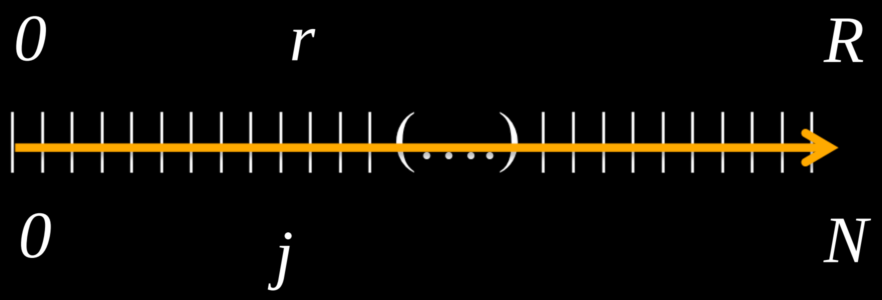


$$\sum_{i=0}^{n} \vec{F}_i = 0$$

$$F_2 - F_1 = \text{peso}$$

$$(P_2 A - P_1 A) = g\,\rho\,(h_2 - h_1)\,A$$

$$P_2 - P_1 = g\,\rho\,(h_2 - h_1)$$



variabile indipendente

Variabili dipendenti: P, T, ρ

$$j = 0, N$$

$$P_{j+1} - P_j = - \frac{G\ m_j}{r_j^2}\ \rho_j\ (r_{j+1} - r_j)$$

Equilibrio idrostatico

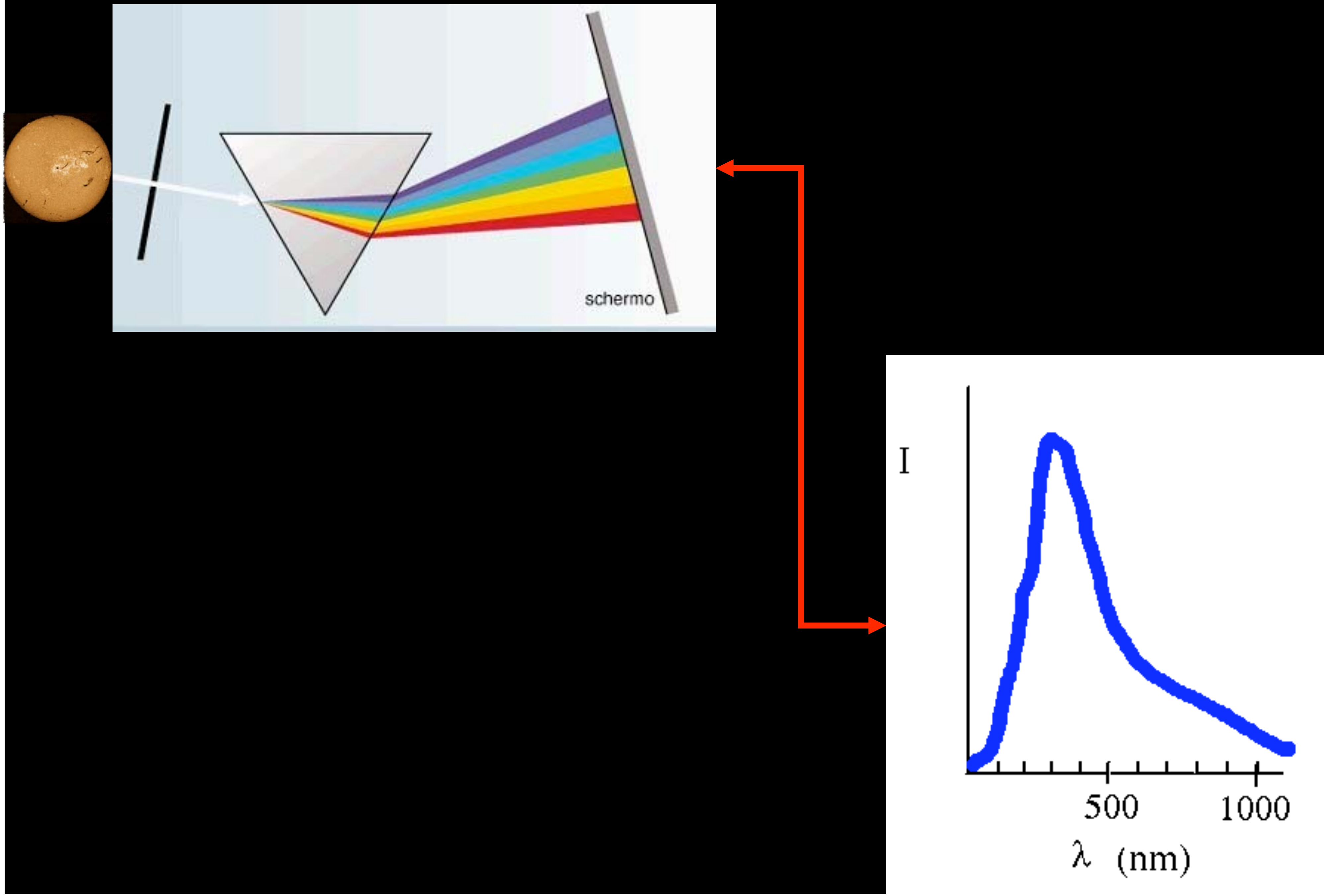
$$P_j = P_j\ (\rho_j,\ T_j)$$

Equazione di stato

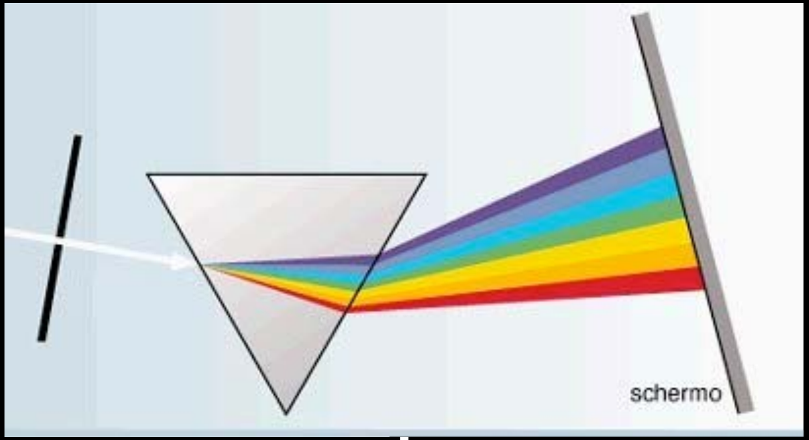
$$m_{j+1} - m_j = 4\ \pi\ \ r_j^2\ \ (r_{j+1} - r_j)\ \rho_j$$

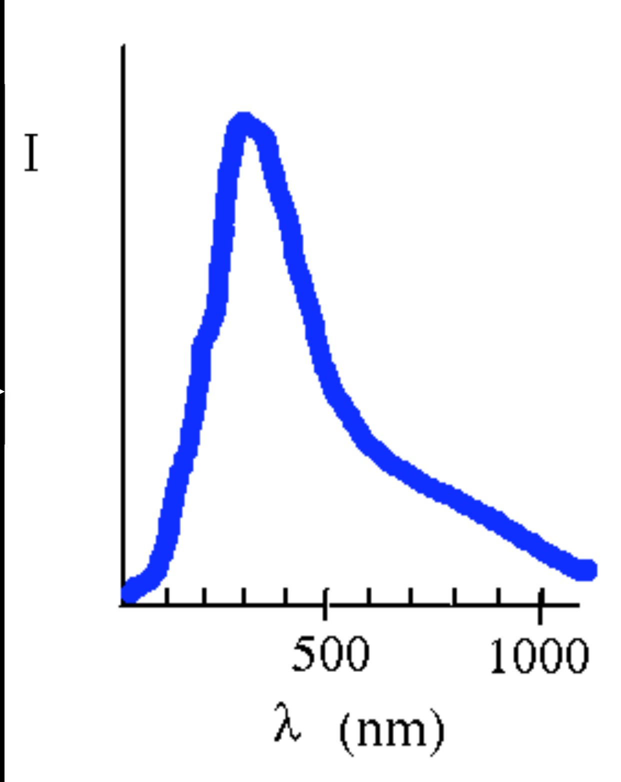
Equazione di continuità

Il Sole come “corpo nero”


schermo
I
500
1000
λ (nm)

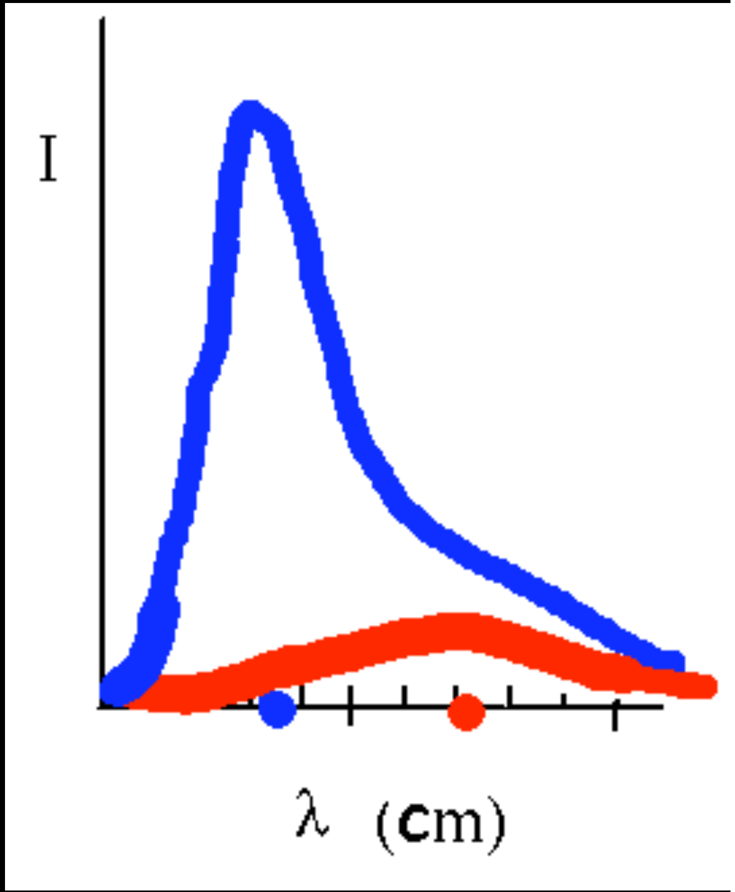
Sorgente
di
luce
bianca





$$\lambda_{max} = \frac{0.2897}{T}$$

λ cm
T Kelvin



Permette di associare
al colore una temperatura

Il Sole emette come se fosse un corpo nero

colore ↔ temperatura

La conservazione dell’energia

(verso l’evoluzione stellare)

La luminosità del Sole

La quantità di energia emessa dal Sole al secondo è:

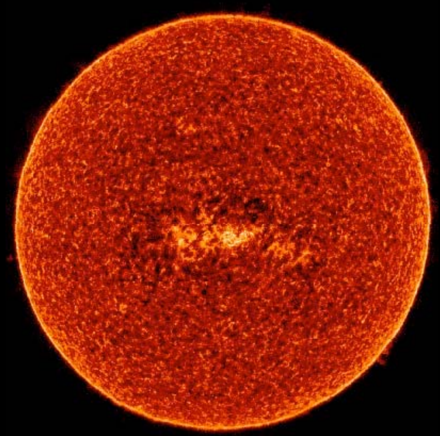
$$L_{sole} \approx 4 \times 10^{26}\ J/s = 4 \times 10^{26}\ W$$

Qual è la sorgente di questa energia?

Un fiammifero si consuma

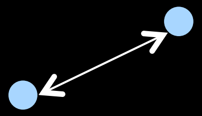
Il Sole si consuma

Ipotesi termodinamica



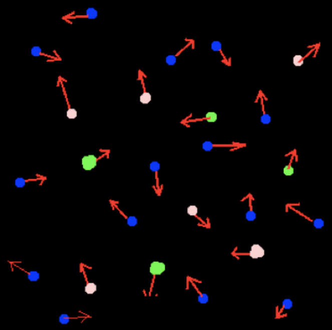
= *gas in interazione gravitazionale*

Energia potenziale gravitazionale



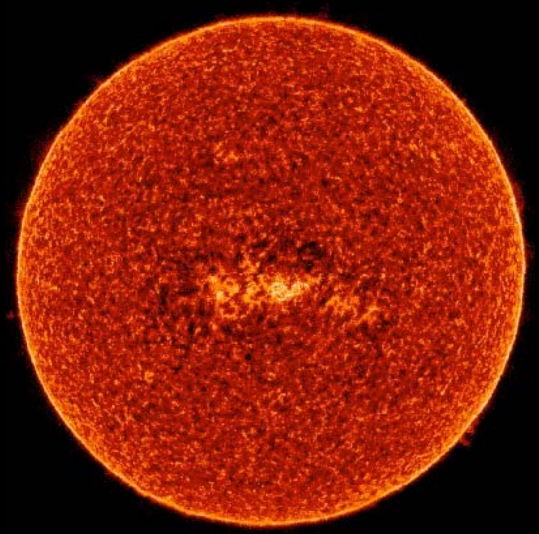
$$U \approx \frac{G\,M^2}{R}$$

Energia cinetica



E_{cin}

$$\frac{1}{2}\frac{d^2 I}{dt^2} = 2\,E_{cin} + U$$

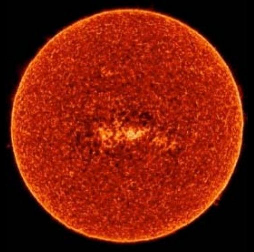


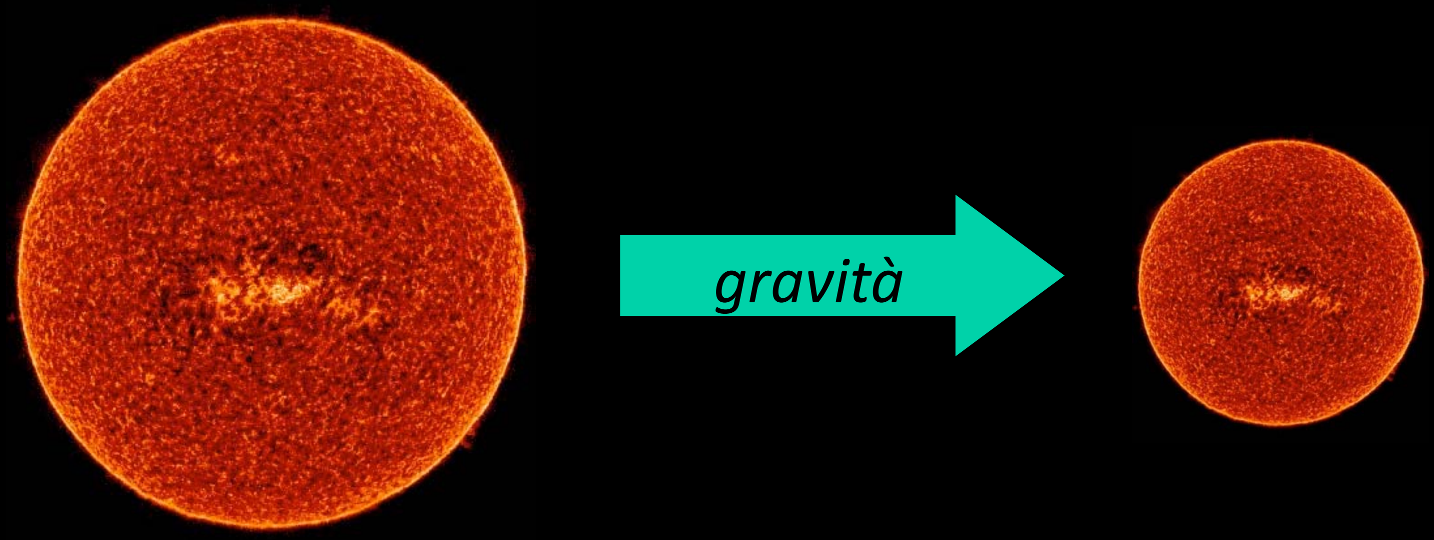
Equilibrio $0 = 2\,E_{cin} + U$

$$2\,\Delta E_{cin} + \Delta U = 0$$

Variazione
equilibrio $\Delta U/2 = -\,\Delta E_{cin}$

$\Delta U/2$ è luce





Quando il sole si contrae sotto l'effetto della

gravità è luminoso

È questa la sorgente di luce
che cerchiamo?

Se il Sole brillasse a causa della contrazione

finirebbe la sua energia potenziale

gravitazionale in pochi anni:

$$t \approx \frac{U}{L} \approx 30\ milioni\ \ di\ anni$$

Ipotesi termonucleare

1948

PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. Bethe
Cornell University, Ithaca, New York
AND
G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

As pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt}=f(t)(\sigma_{i-1}n_{i-1}-\sigma_i n_i) \quad i=1,2,\cdots 238, \tag{1}$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm³.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho\cong10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty}(10^6/t^2)dt\cong5\times10^4, \tag{2}$$

which gives us $t_0\cong20$ sec. and $\rho_0\cong2.5\times10^5$ g sec./cm³. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^5 g sec./cm³ which can possibly be understood if we

Fig. 1.
Log of relative abundance
Atomic weight

1957

REVIEWS OF
MODERN PHYSICS

Volume 29, Number 4 October, 1957

Synthesis of the Elements in Stars*

E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle
Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

TABLE OF CONTENTS

Page
I. Introduction 548
  A. Element Abundances and Nuclear Structure 548
  B. Four Theories of the Origin of the Elements 550
  C. General Features of Stellar Synthesis 550
II. Physical Processes Involved in Stellar Synthesis, Their Place of Occurrence, and the Time-Scales Associated with Them 551
  A. Modes of Element Synthesis 551
  B. Method of Assignment of Isotopes among Processes (i) to (viii) 553
  C. Abundances and Synthesis Assignments Given in the Appendix 555
  D. Time-Scales for Different Modes of Synthesis 556
III. Hydrogen Burning, Helium Burning, the α Process, and Neutron Production 559
  A. Cross-Section Factor and Reaction Rates 559
  B. Pure Hydrogen Burning 562
  C. Pure Helium Burning 565
  D. α Process 567
  E. Succession of Nuclear Fuels in an Evolving Star 568
  F. Burning of Hydrogen and Helium with Mixtures of Other Elements; Stellar Neutron Sources 569
IV. e Process 577
V. s and r Processes: General Considerations 580
  A. "Shielded" and "Shielding" Isobars and the s, r, p Processes 580
  B. Neutron-Capture Cross Sections 581
  C. General Dynamics of the s and r Processes 583
VI. Details of the s Process 583

---

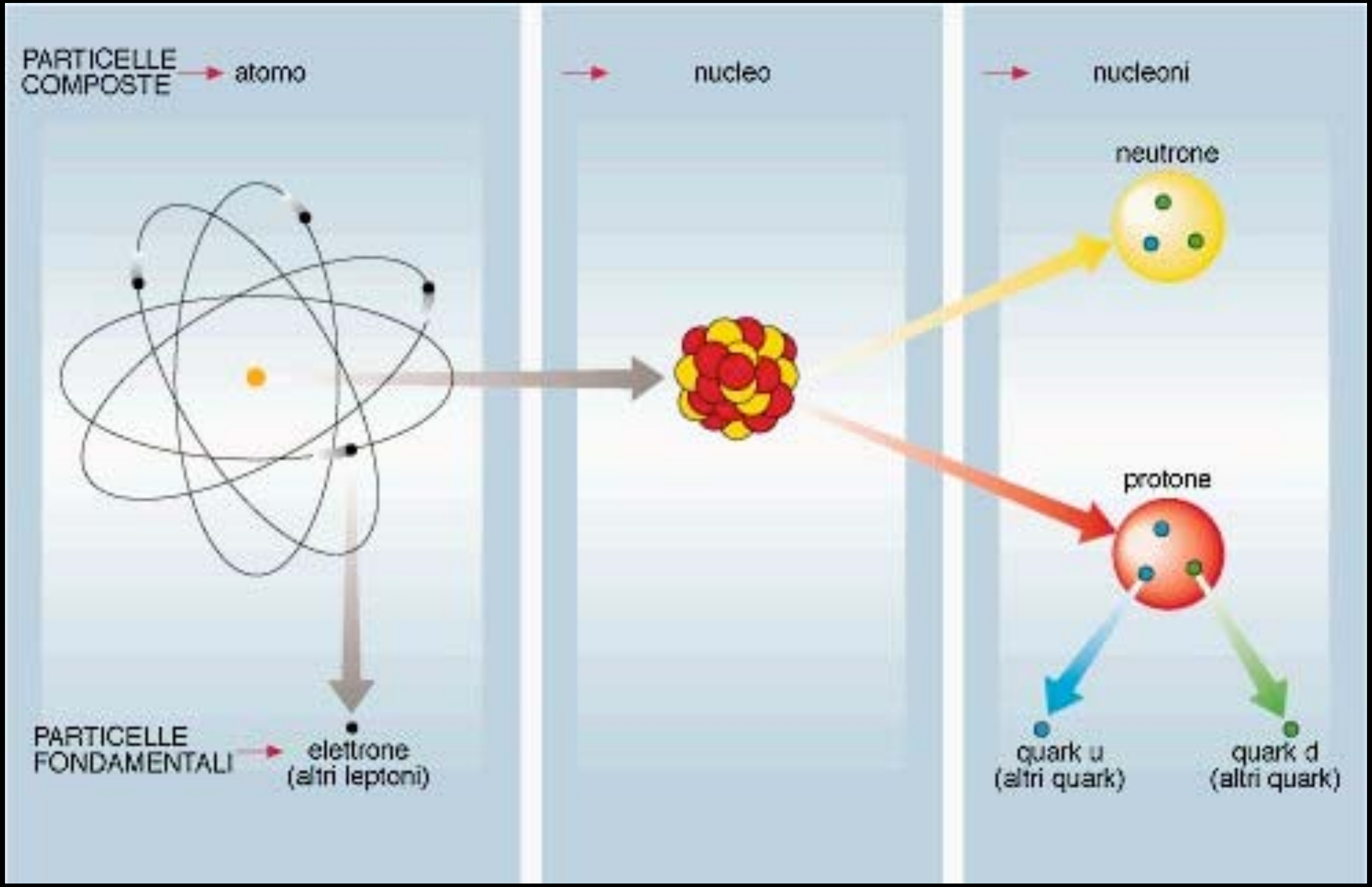
* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

Viaggio all’interno del Sole

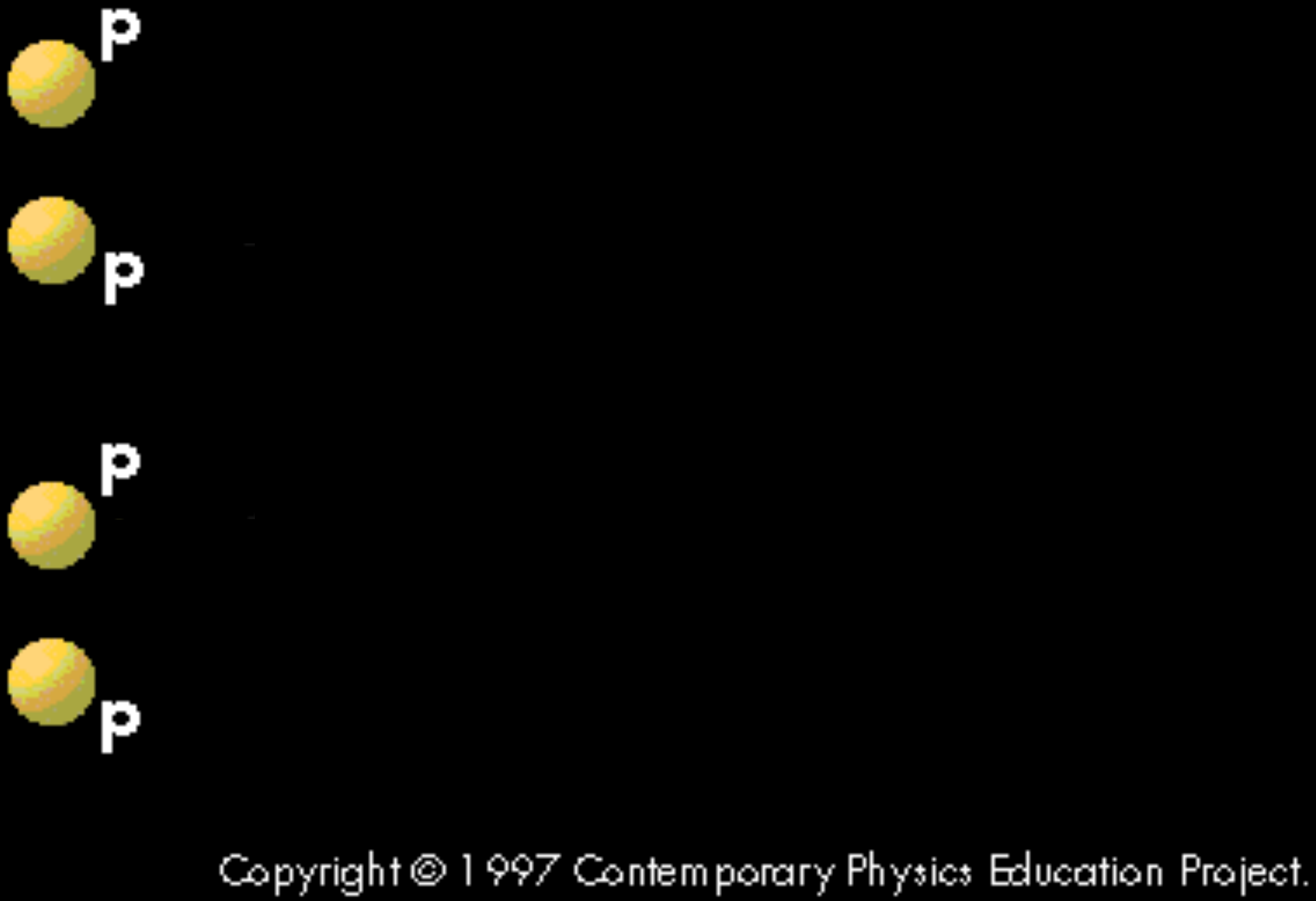
esa

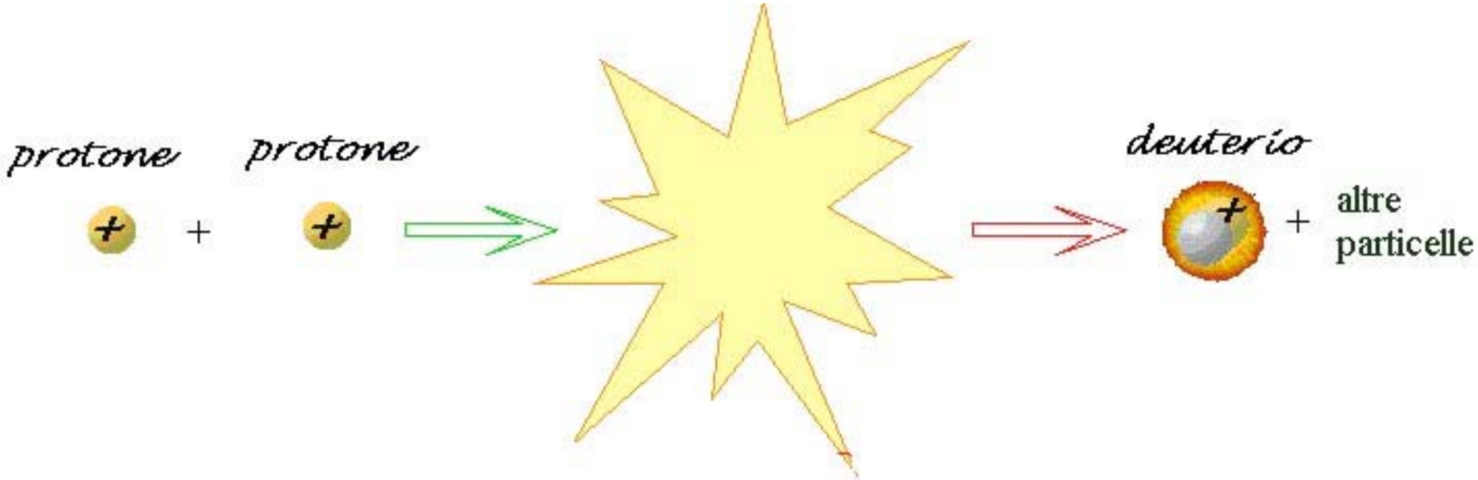
www.spacetelescope.org

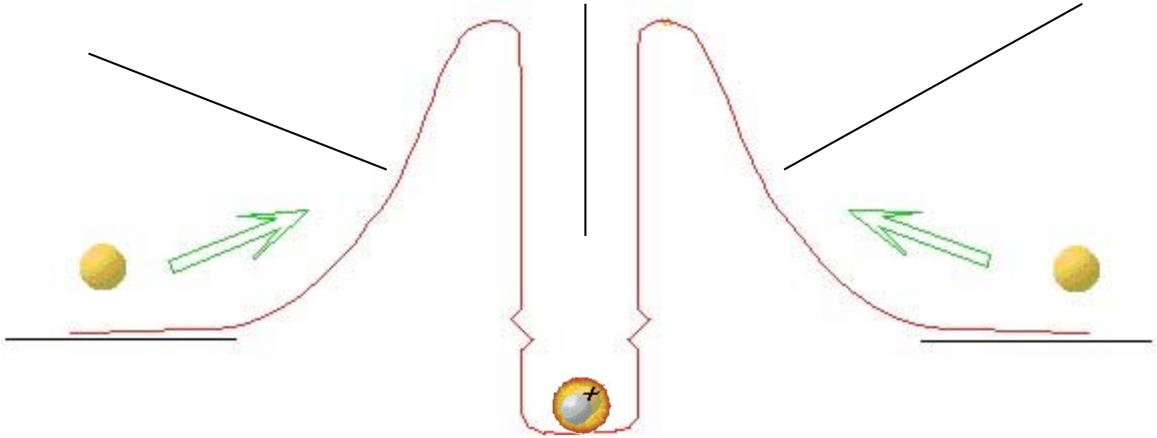
Le reazioni nucleari



La catena protone protone





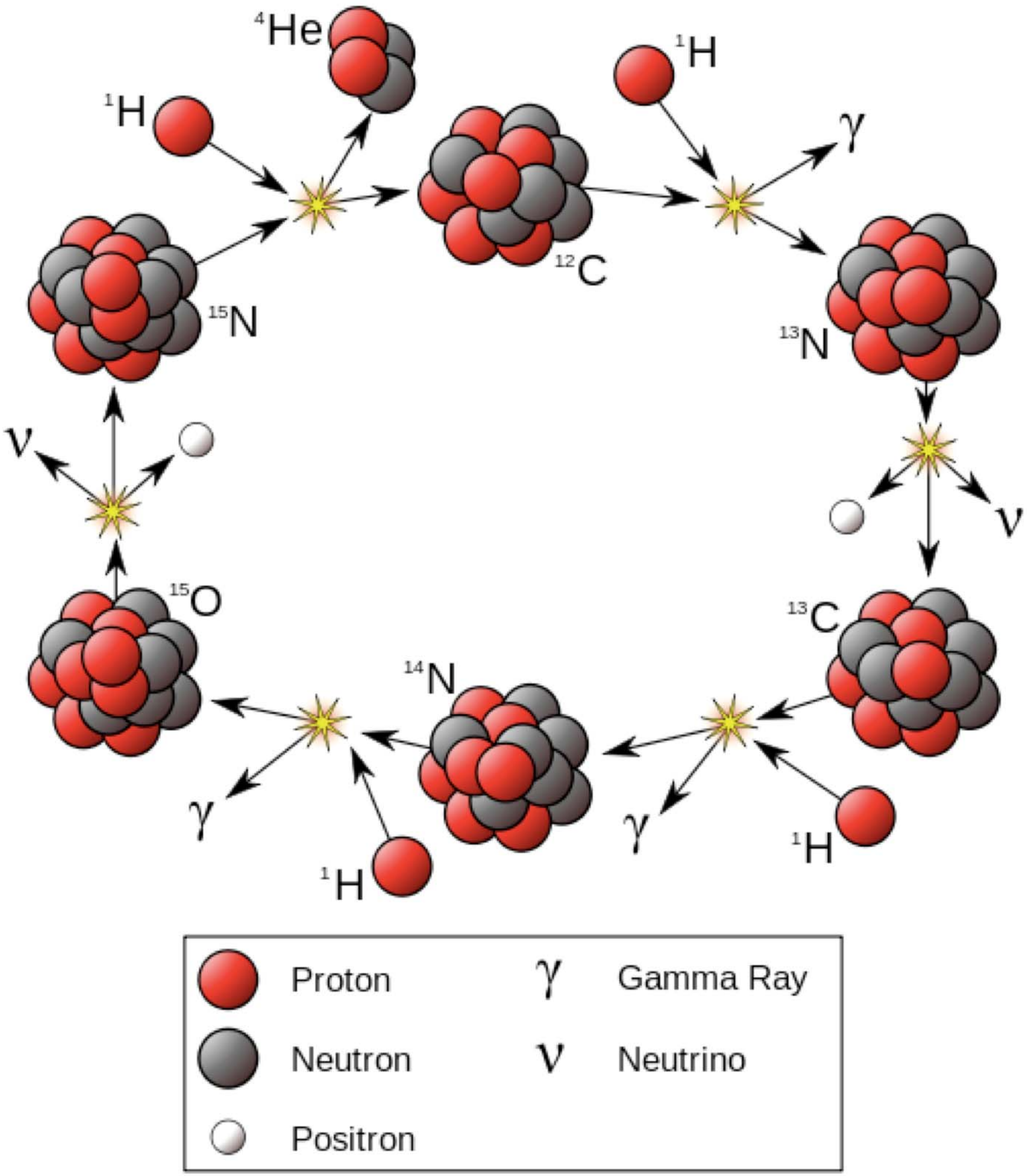


Repulsione elettrostatica

Interazione nucleare

Repulsione elettrostatica

La catena protone protone


^{4}He
^{1}H
^{1}H
γ
^{12}C
^{15}N
^{13}N
ν
ν
^{15}O
^{13}C
^{14}N
γ
γ
^{1}H
^{1}H
Proton
γ Gamma Ray
Neutron
ν Neutrino
Positron

Massa di 1 protone

$= 1{,}673 \times 10^{-27}$ Kg

Massa di 1 neutrone

$= 1{,}675 \times 10^{-27}$ Kg

Massa di 2 protoni + 2 neutroni

$= 6{,}695 \times 10^{-27}$ Kg

Massa di 1 nucleo di Elio (He)

$= 6{,}646 \times 10^{-27}$ Kg

Perché questa differenza? Energia di legame

Nella catena p-p,

4 H → 1 He

Massa di 4 atomi di idrogeno (4H)

$= 6,690 \times 10^{-27}$ Kg

Massa di 1 atomo di Elio (He)

$= 6,646 \times 10^{-27}$ Kg

Differenza di Massa

= (massa 4 atomi di H) - (massa 1 atomo di He)

$= 0.044 \times 10^{-27}$ Kg

$E = \text{MASSA} \times c^2$

Quindi: ENERGIA LIBERATA nella FUSIONE

= (**Differenza di Massa**) x c^2

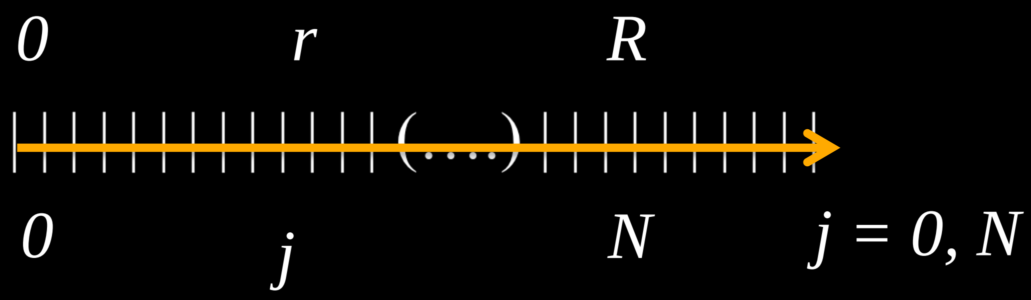
= 4.22×10^{-12} Joule

energia liberata per un grammo di materia

= 6.30×10^{11} Joule

Es. 1: calcolare l'equivalente in barattoli di nutella

Es. 2: Calcolare la durata del Sole nell'ipotesi di consumo completo



0 r R

$(\ldots)$

0 j N $j = 0, N$

$\varepsilon_j = \varepsilon_j\,(\rho_j, T_j)$

$L_{j+1} - L_j = 4\,\pi\ \ r_j^2\ (r_{j+1} - r_j)\ \rho_j\ \varepsilon_j$ conservazione energia

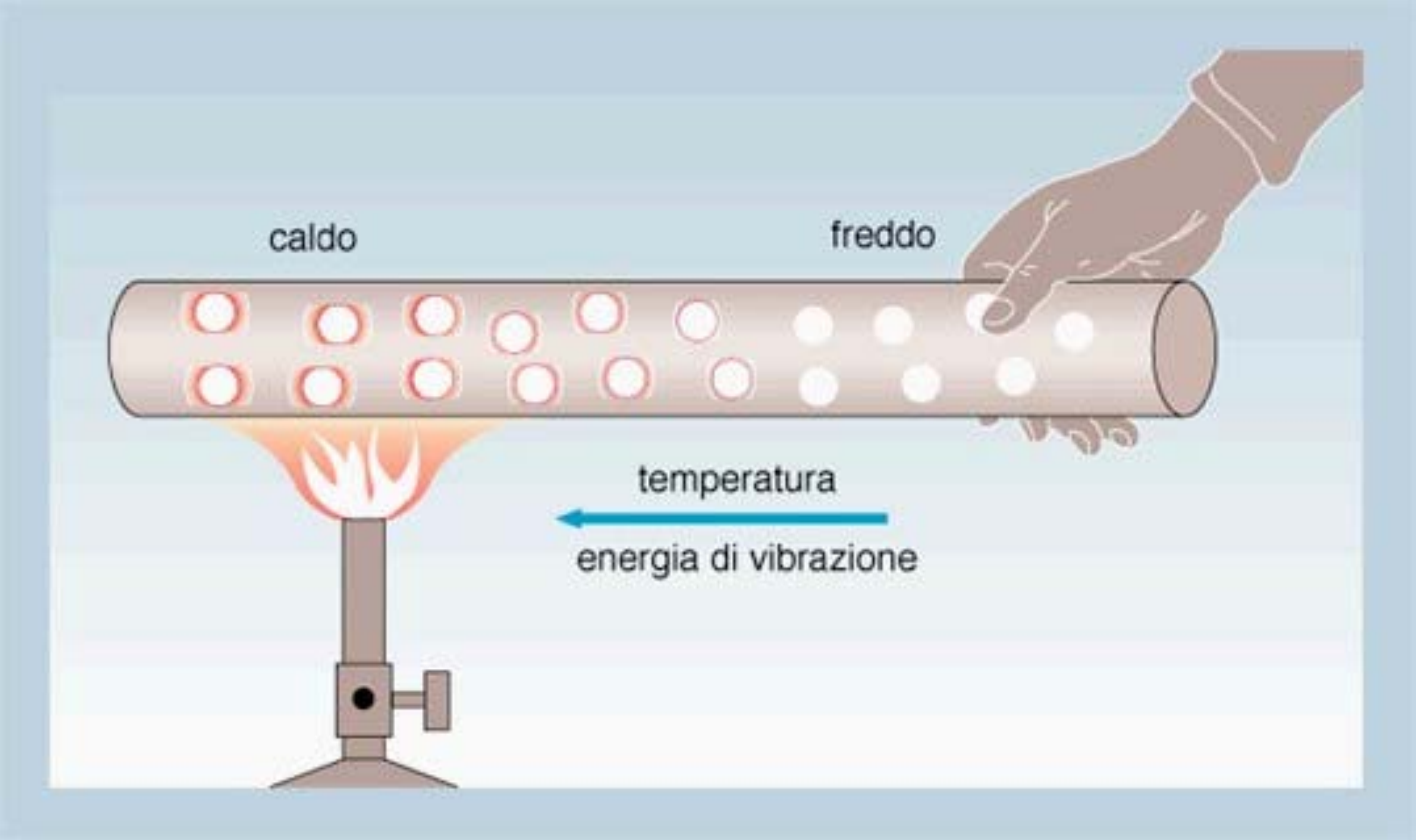
$\kappa_j = \kappa_j\,(\rho_j, T_j)$

Trasporto di energia

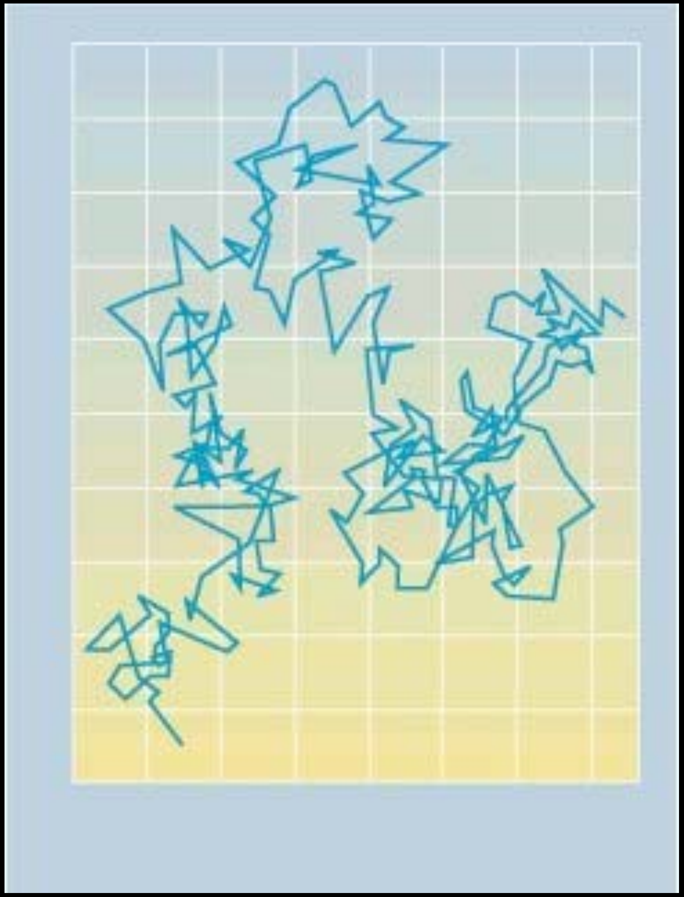
$T_{j+1} - T_j = \dots$

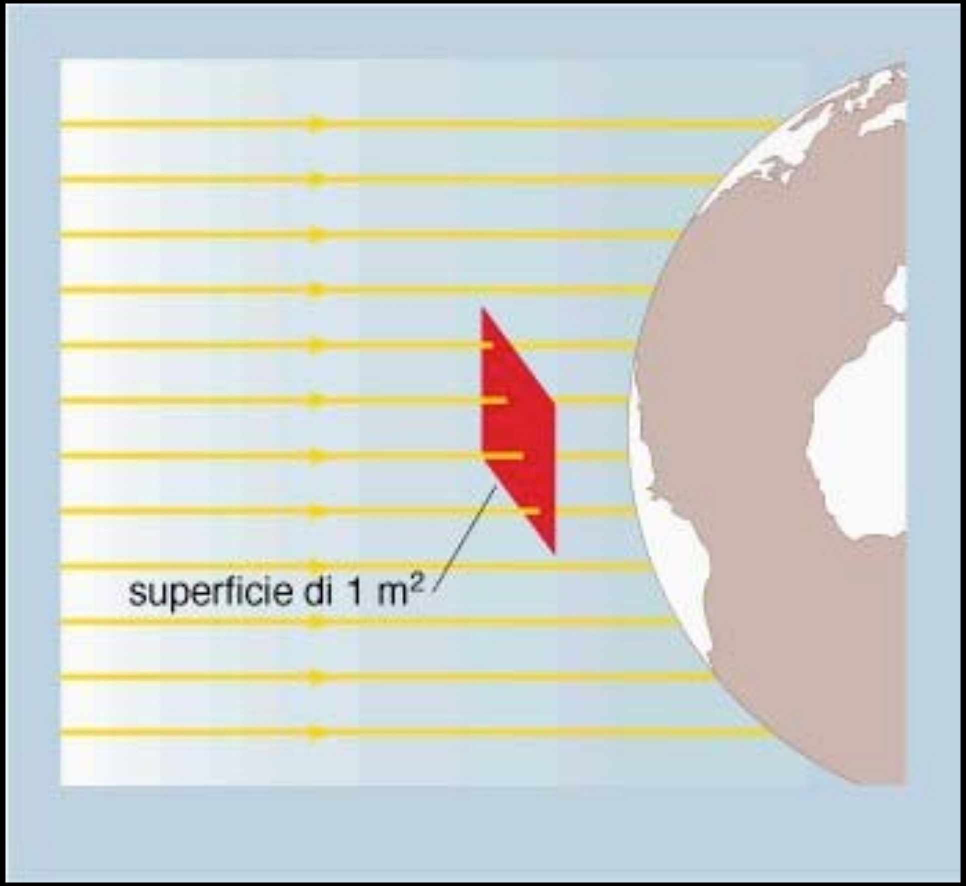
equazione del trasporto

Trasporto energia 1: la conduzione

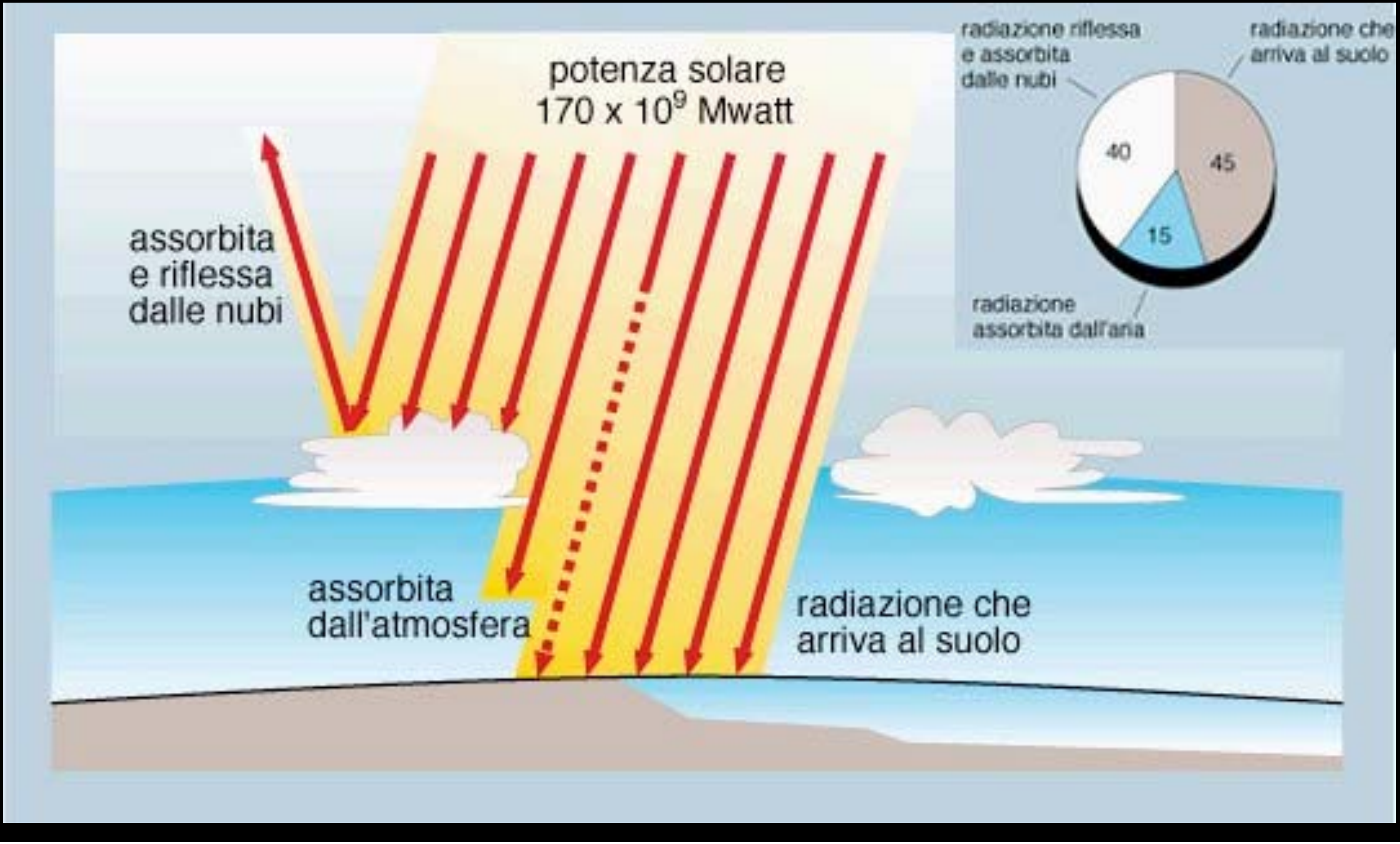


Trasporto energia 2: l’irraggiamento



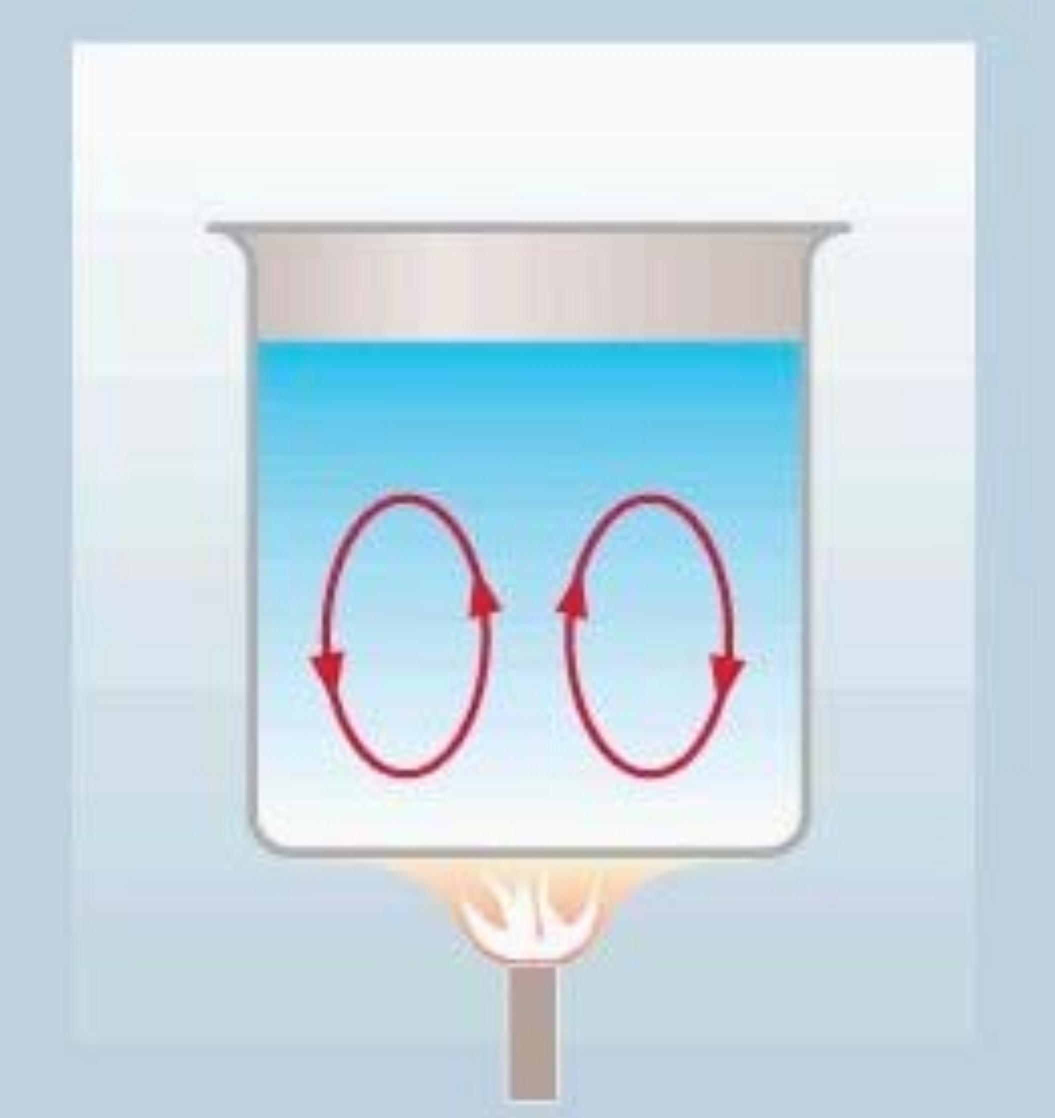


Trasporto energia 2: l'irraggiamento



Trasporto energia 3: la convezione

Trasporto energia 3: la convezione

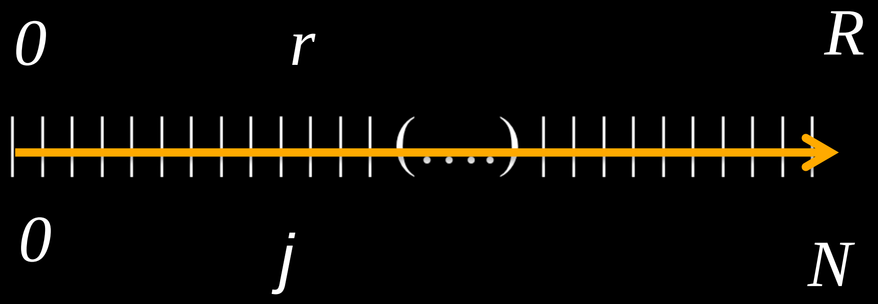


Trasporto energia: sintesi

Conduzione	solo nei solidi
Irraggiamento	meccanismo principale
Convezione	meccanismo di «troppo pieno»

$T_{j+1}-T_j = \ldots$ equazione del trasporto

Stelle di carta



$j = 0, N$

$$P_{j+1} - P_j = - \frac{G\, m_j}{r_j^2}\, \rho_j\, (r_{j+1} - r_j)$$ Equilibrio idrostatico

$$m_{j+1} - m_j = 4\, \pi\, r_j^2\, (r_{j+1} - r_j)\, \rho_j$$ Equazione di continuità

$$L_{j+1} - L_j = 4\, \pi\, r_j^2\, (r_{j+1} - r_j)\, \rho_j\, \varepsilon_j$$ Conservazione energia

$$T_{j+1} - T_j = \ldots$$ Equazione del trasporto

$\varepsilon_j = \varepsilon_j\, (\rho_j, T_j)$ $\kappa_j = \kappa_j\, (\rho_j, T_j)$ $P_j = P_j\, (\rho_j, T_j)$

Un'idea di Felix