



L'universo in fiore

*L'astronomia costringe l'anima a guardare oltre
e ci conduce da un mondo ad un altro»
La Repubblica - Platone*

*Corso di astronomia 2013-2014
Osservatorio Astronomico di Brera*



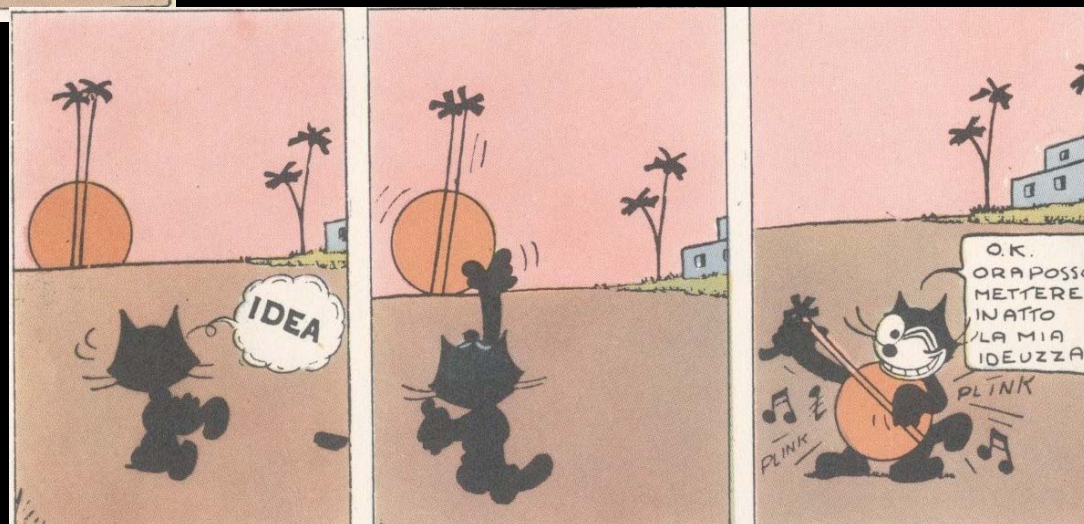
Il sole e le reazioni nucleari

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

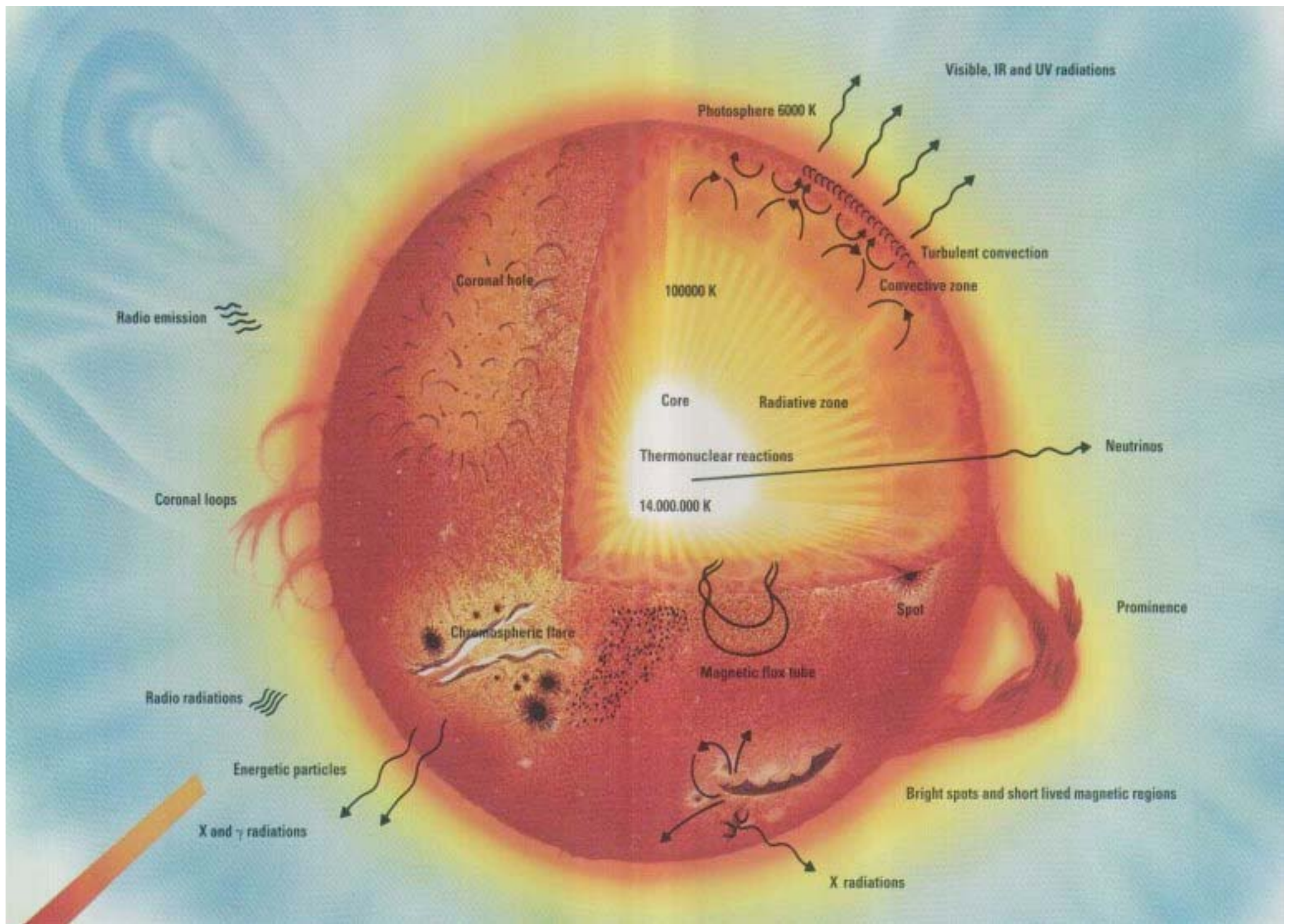
- <http://www.nasa.gov/missions/current/index.html> : tutte le missioni spaziali attive, con descrizioni e links alle loro pagine web: per il Sole vedi Hinode, Rhesi, Soho, Stereo, Trace, SDO
- <http://spaceweather.com/> Informazioni in tempo reale sull'attività solare
- D. Whitehouse; Il Sole: una biografia; 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)



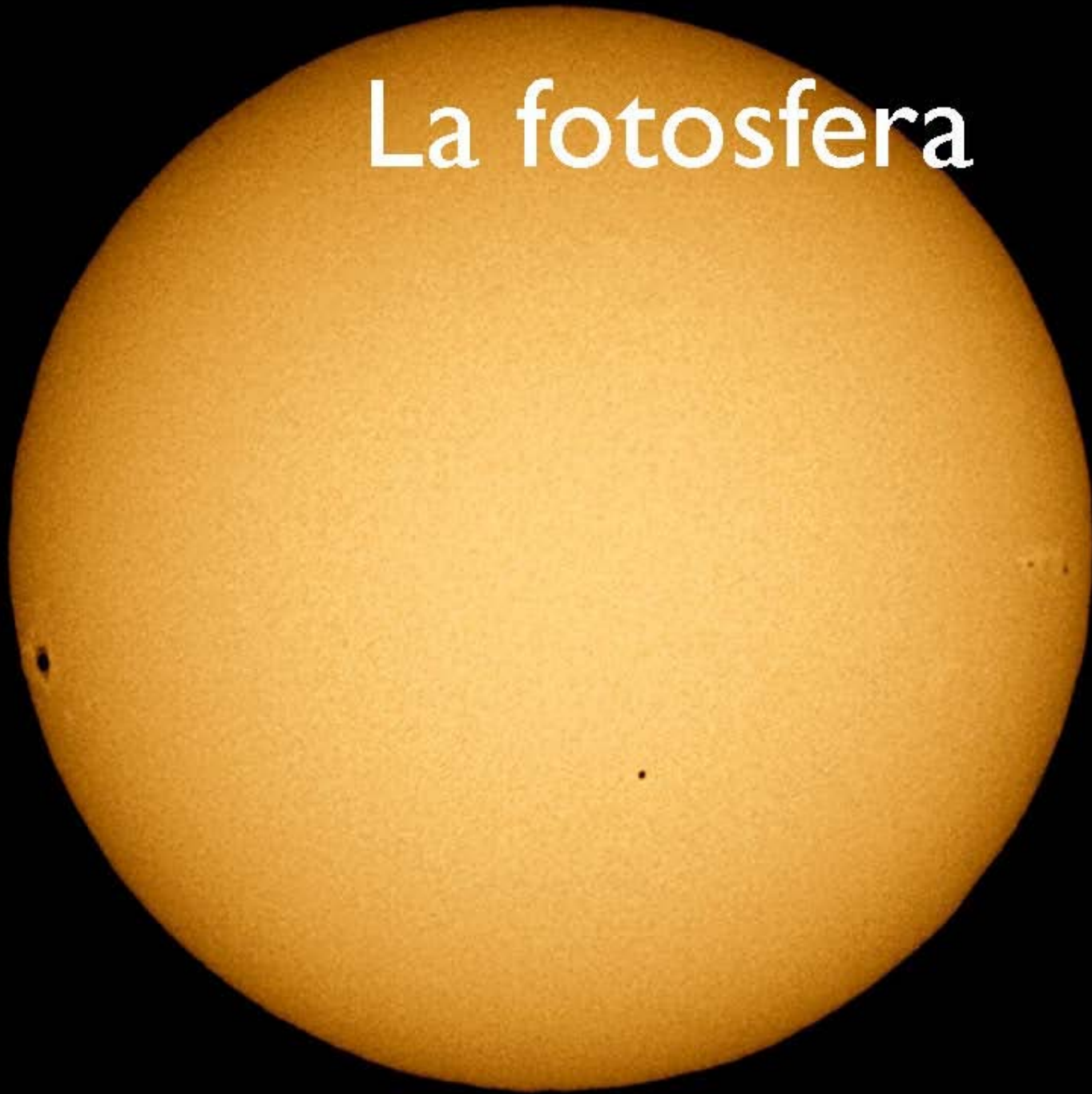
La corona solare



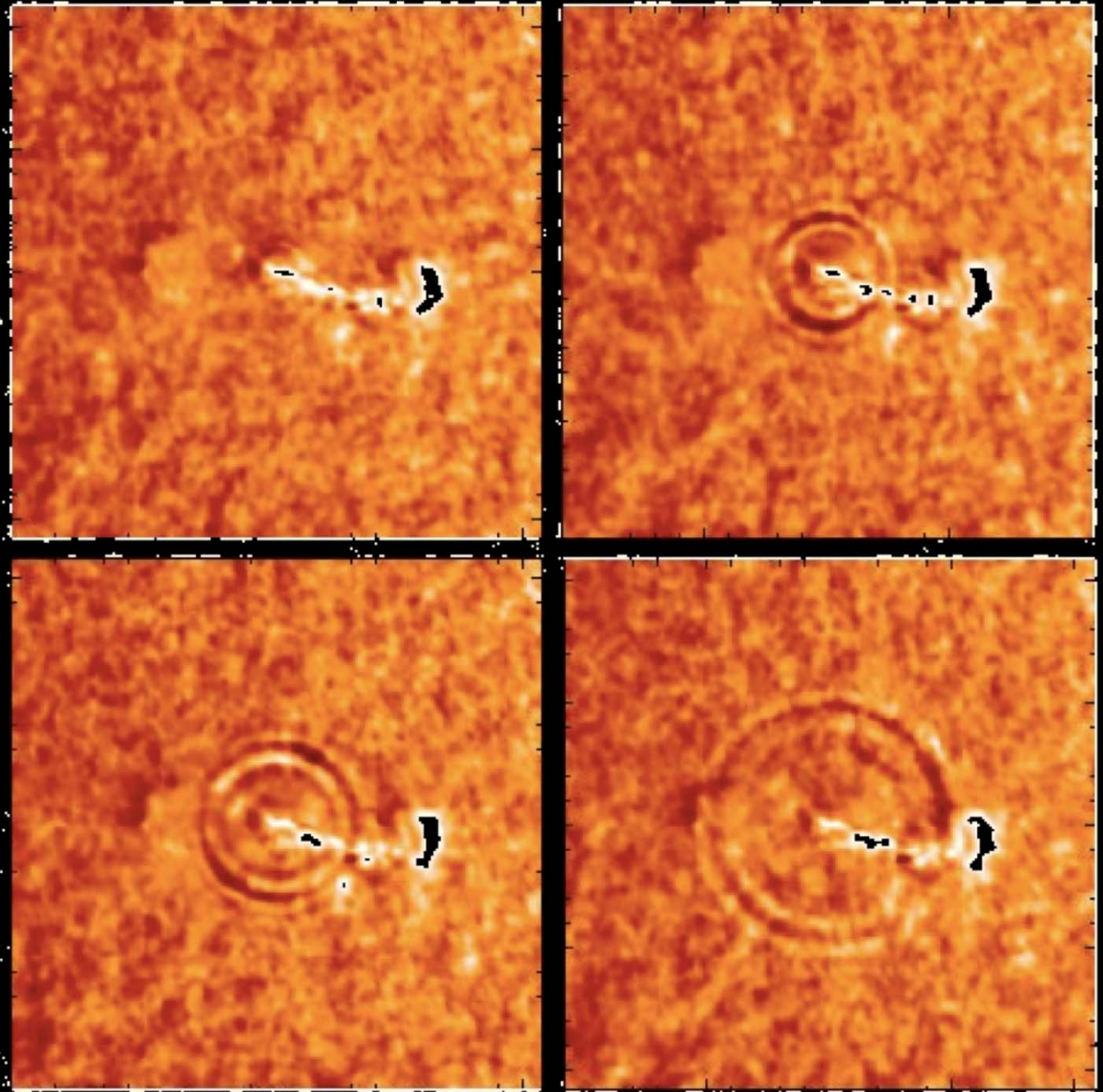
La cromosfera



La fotosfera

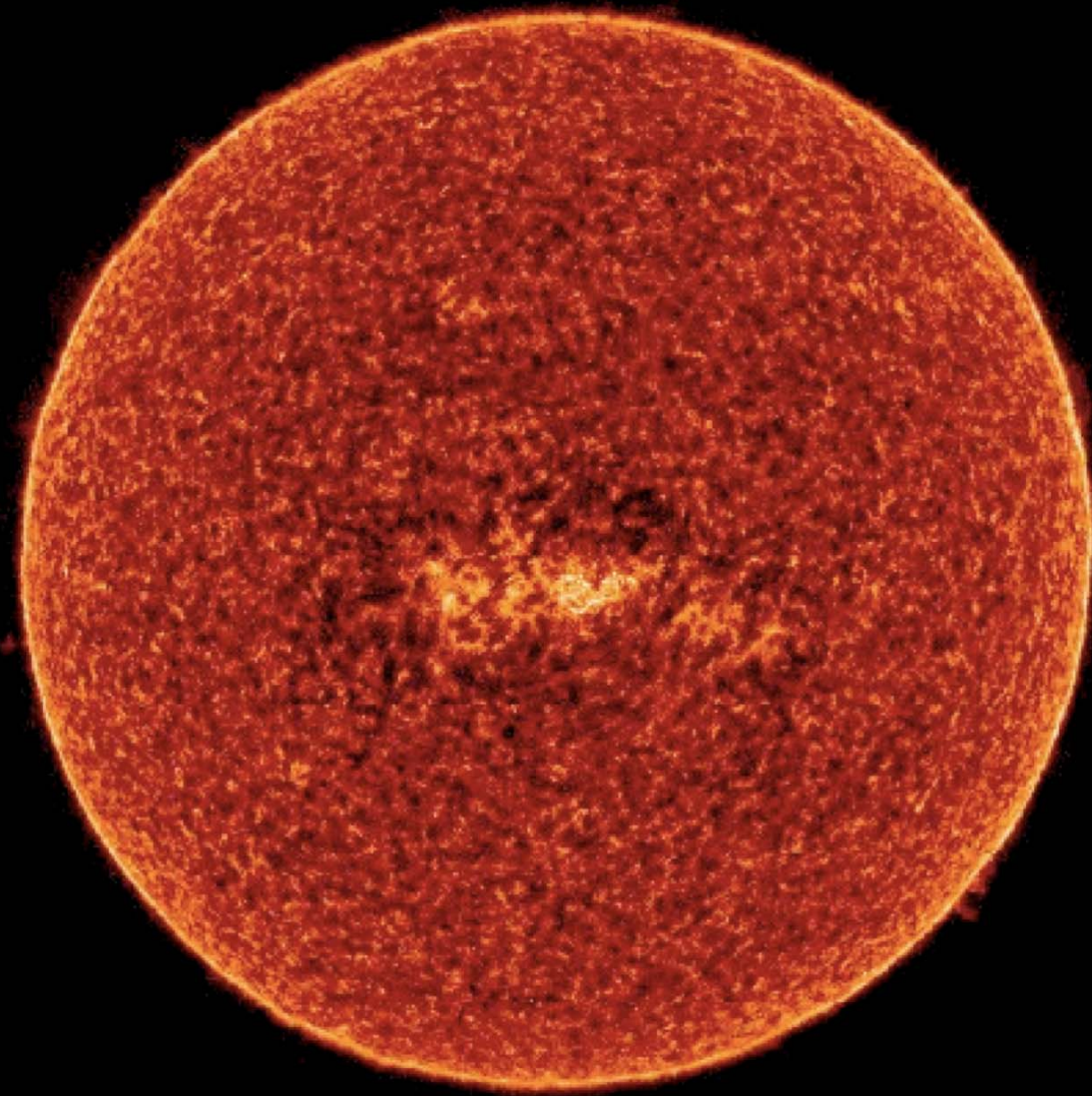


solemoto



Granulazione

un Sole che bolle



SOHO (NASA/ESA)

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

ISTORIA
E DIMOSTRAZIONI
INTORNO ALLE MACCHIE SOLARI
E LORO ACCIDENTI

COMPRESSE IN TRE LETTERE SCRITTE
ALL' ILLVSTRISSIMO SIGNOR
MARCO VELSERI LINCEO
DVVM VIRO 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.*

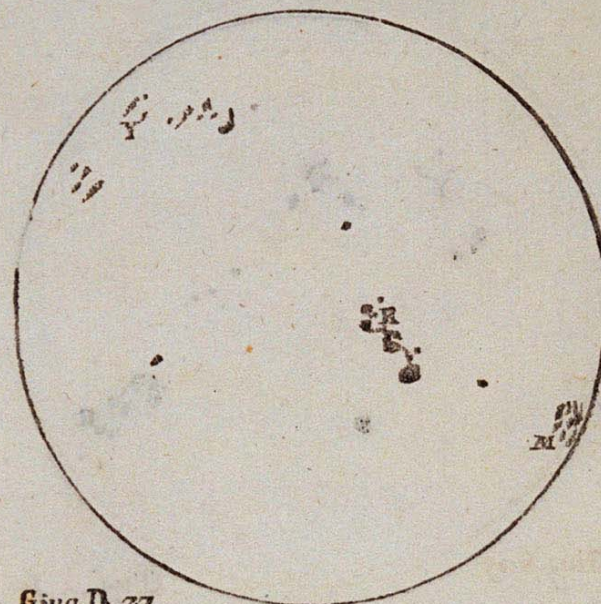
Si aggiungono nel fine le Lettere, e Disquisizioni del finto Apelle.



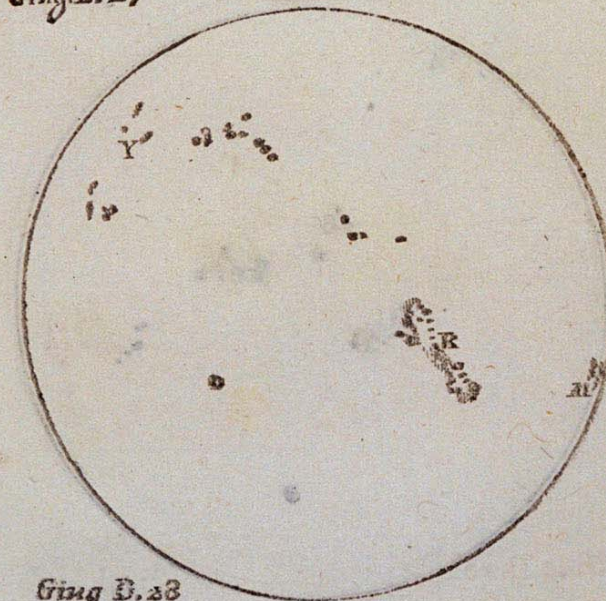
IN ROMA, Appresso Giacomo Mascardi. MDCXIII.
CON LICENZA DE' SUPERIORI.

DEL SIG. GALILEE

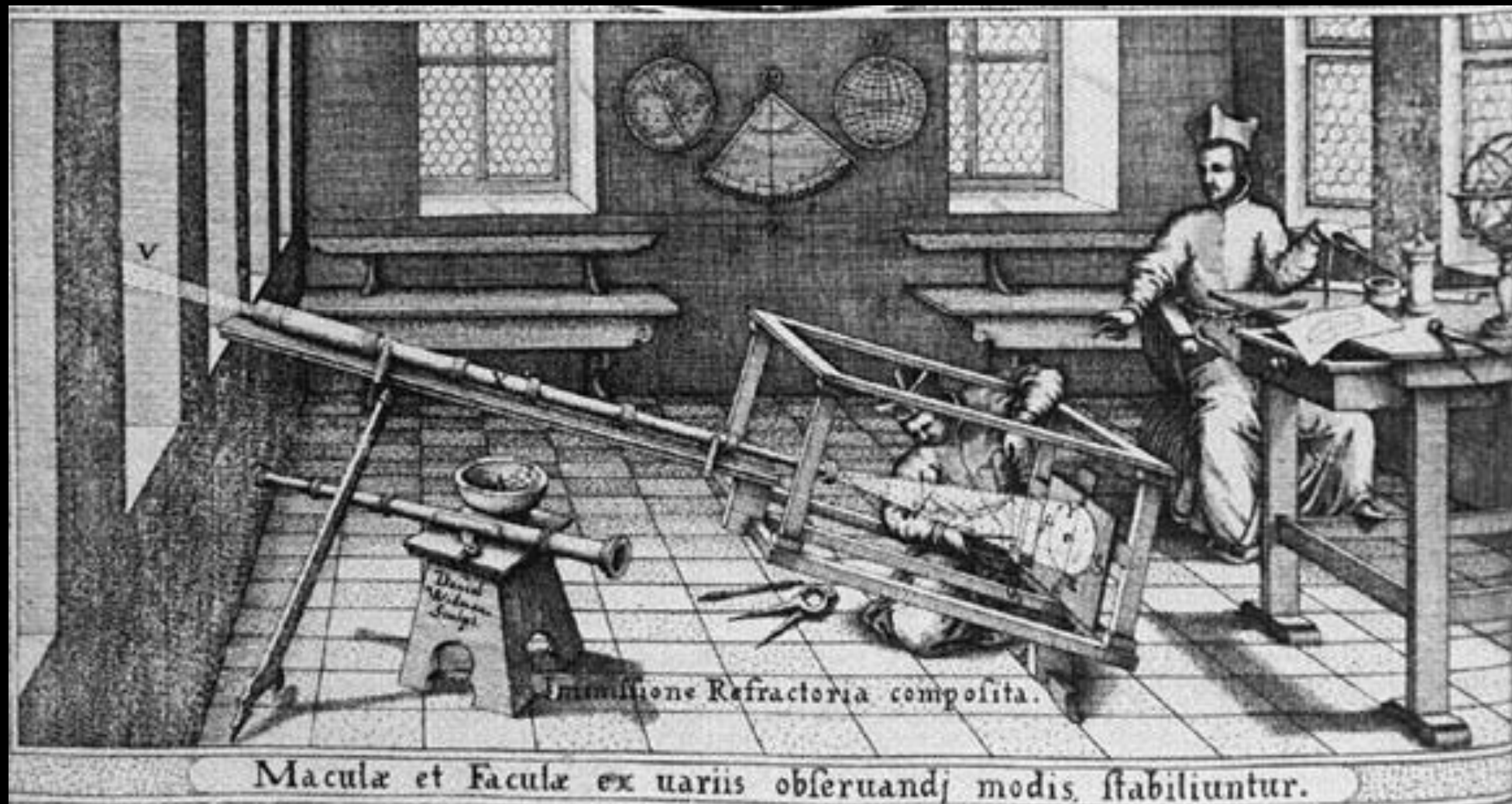
museo
galileo



Ging. D. 27



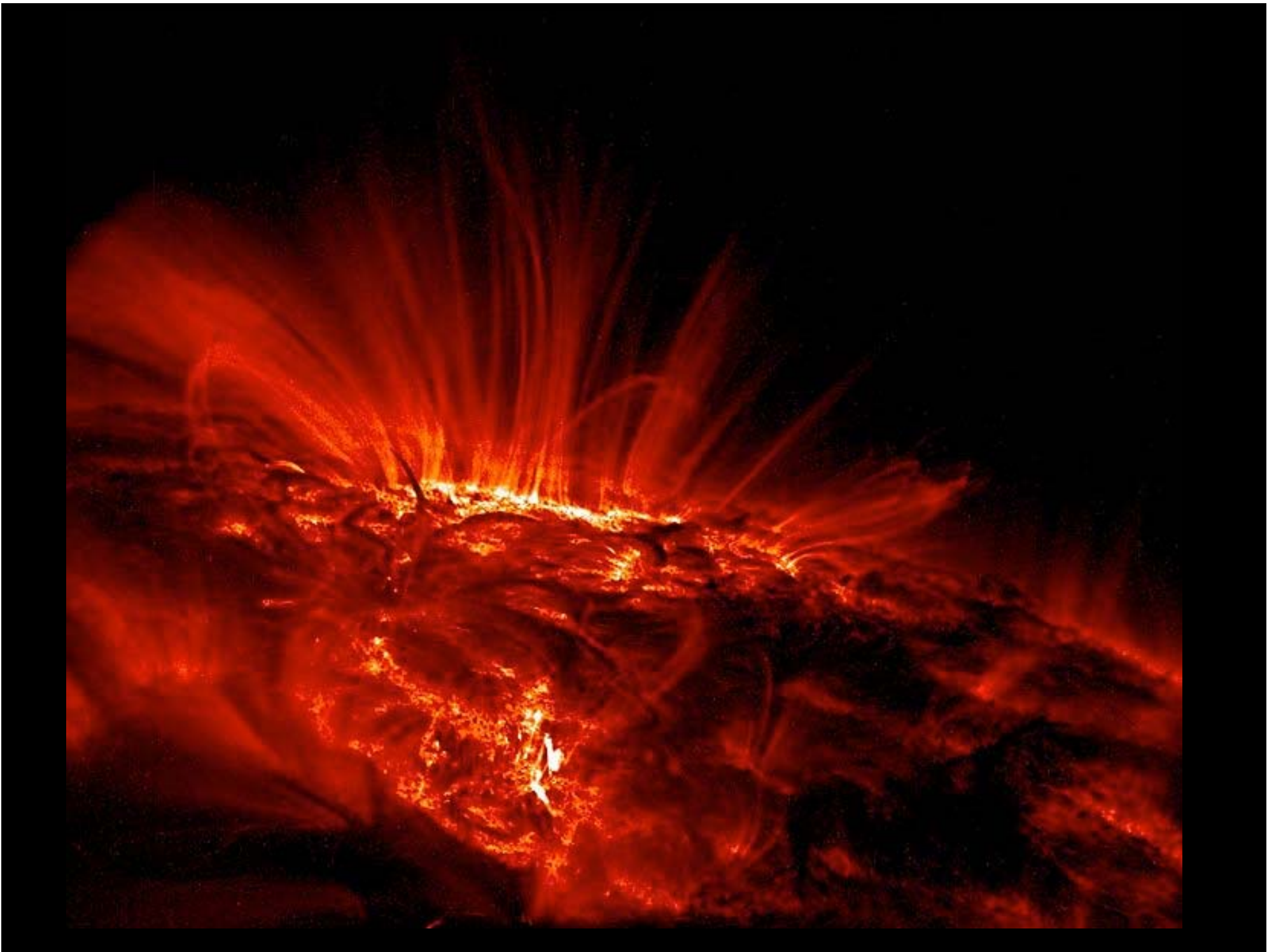
Ging. D. 28



La fotosfera: macchie e facole



2001/03/27 12:48 UT

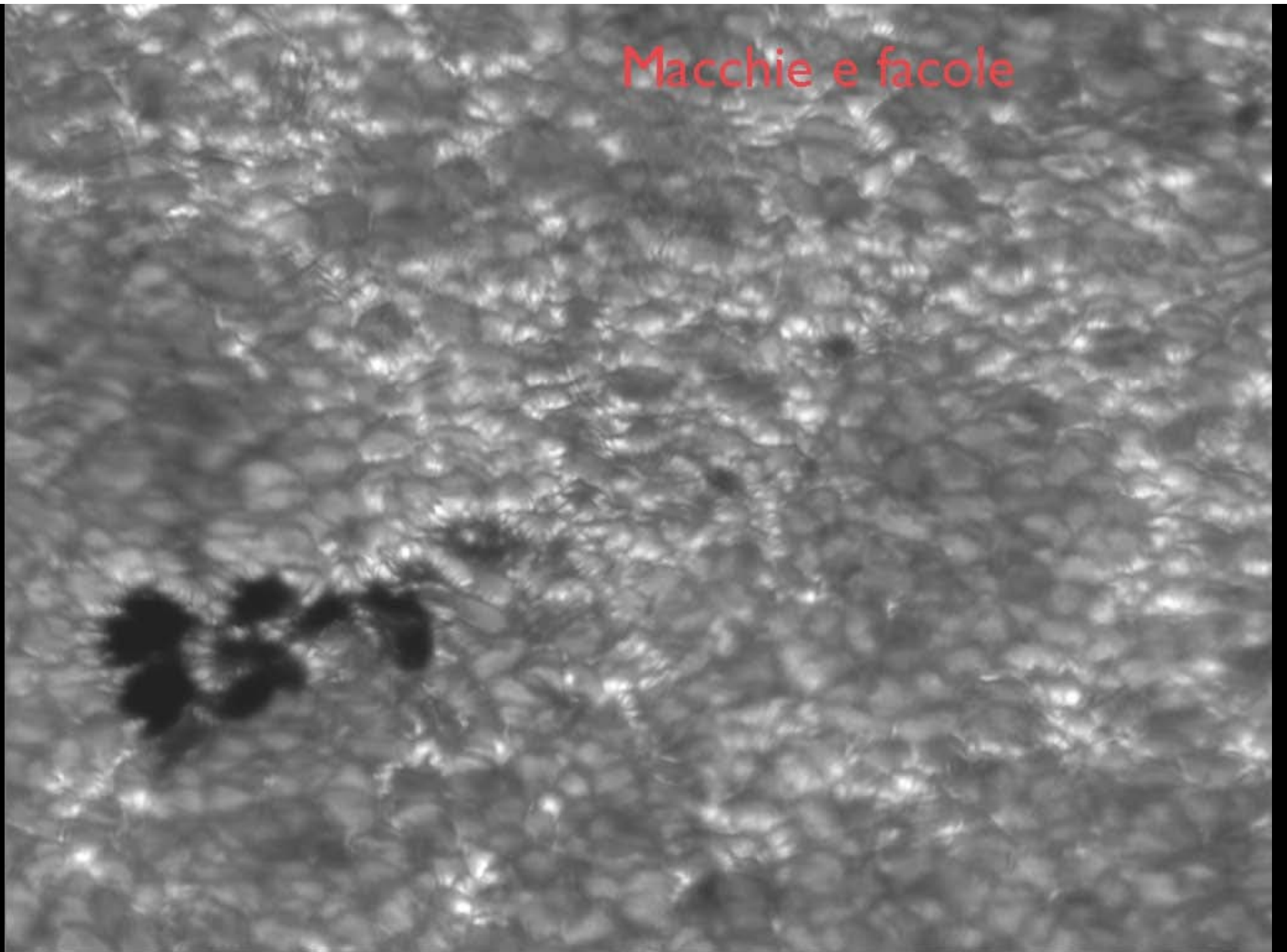


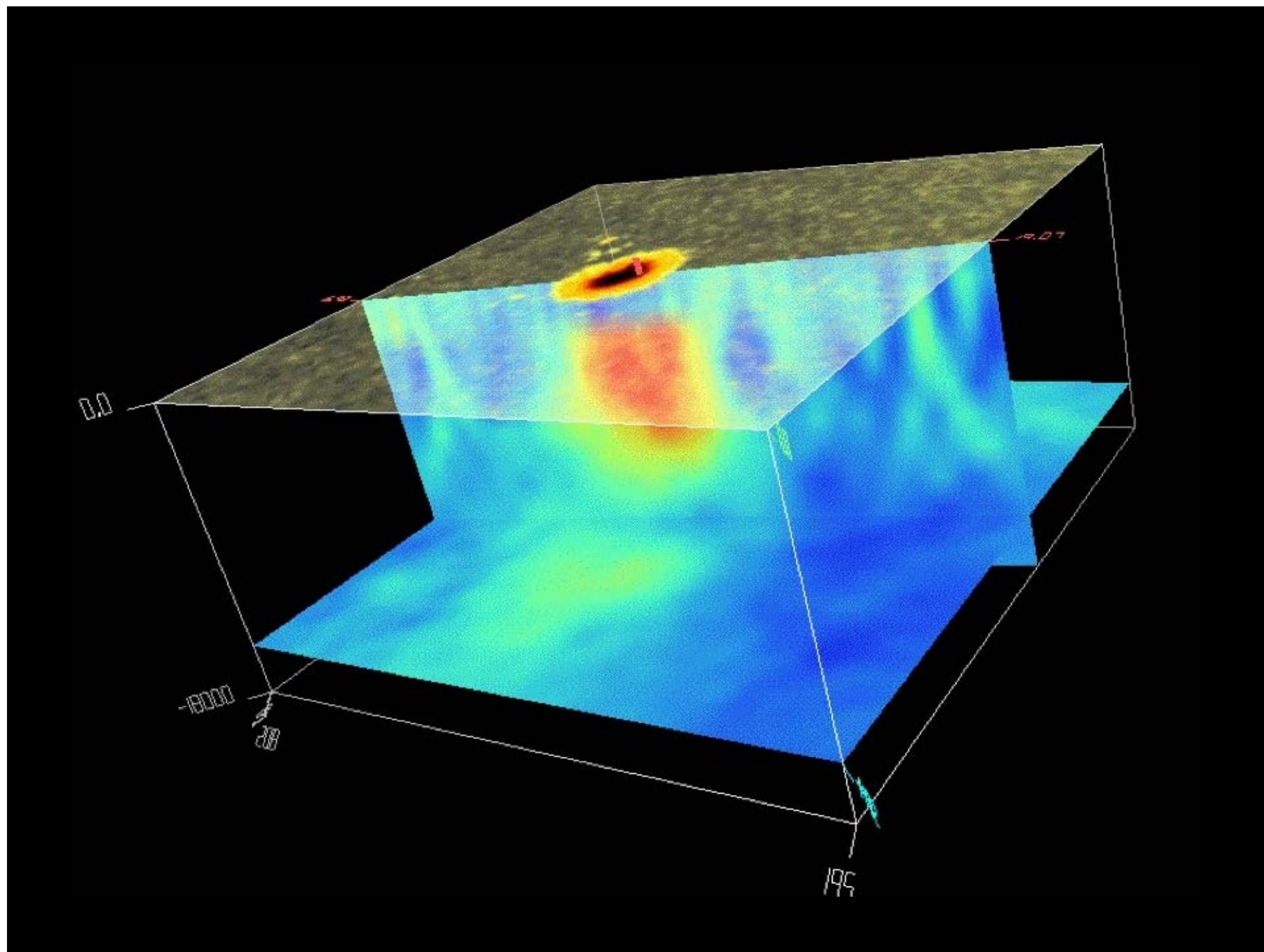


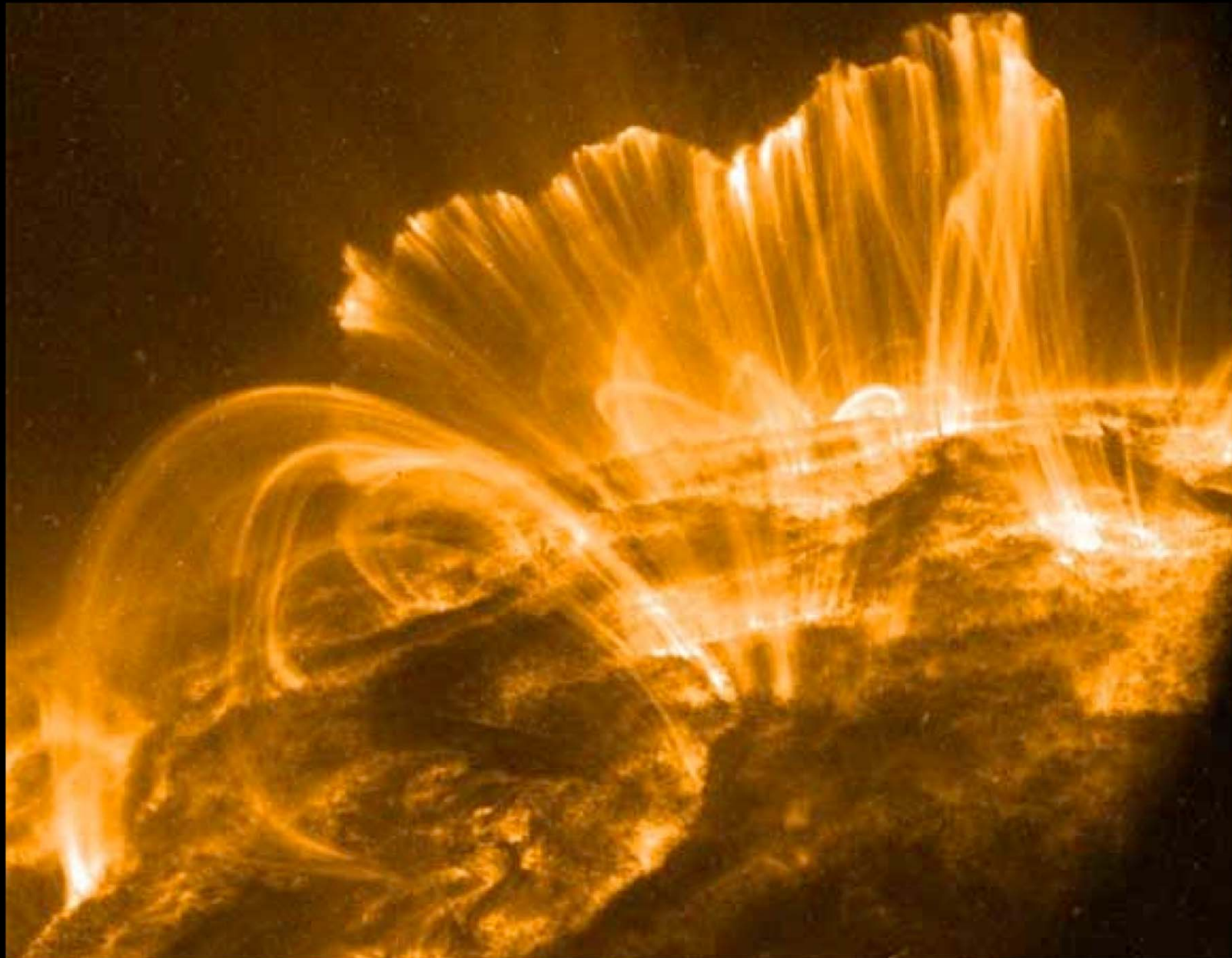
Le macchie solari

Wednesday 19 December 2012

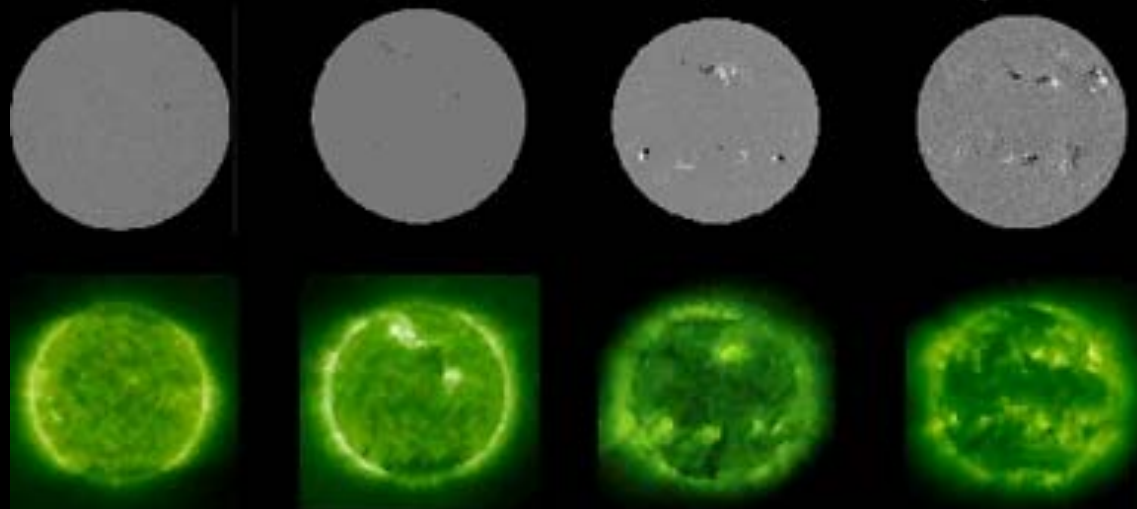
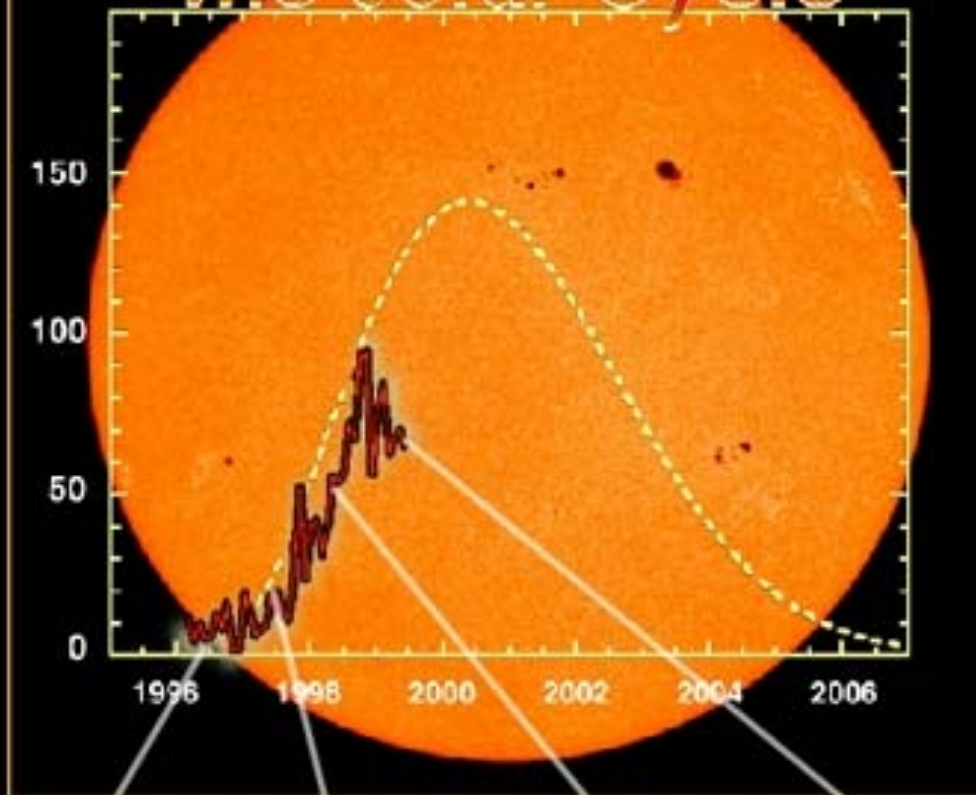
Macchie e facole

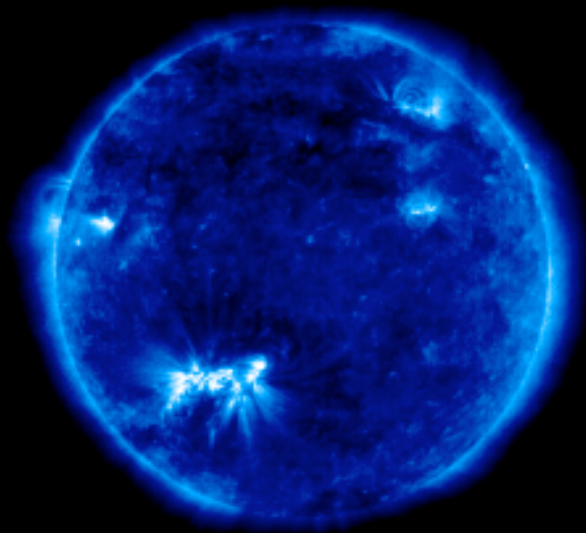






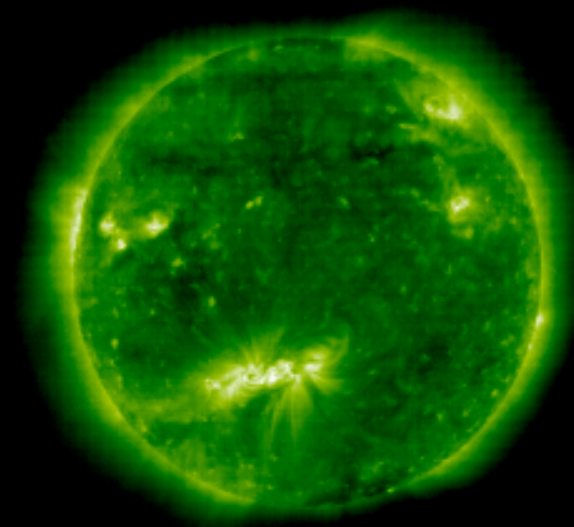
The Solar Cycle





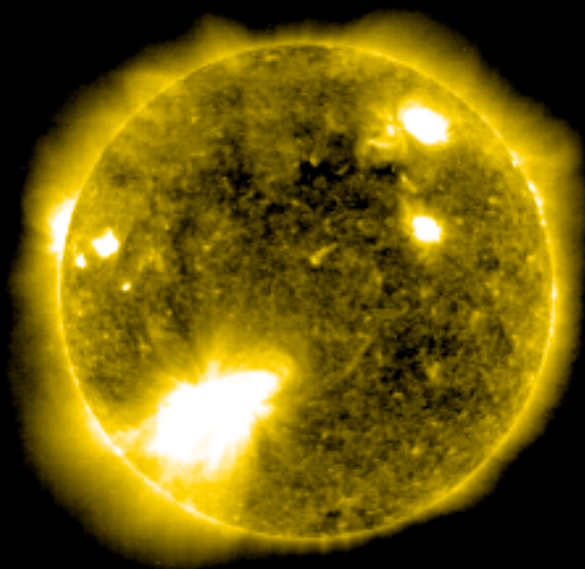
2010/11/09 01:00

171 Å



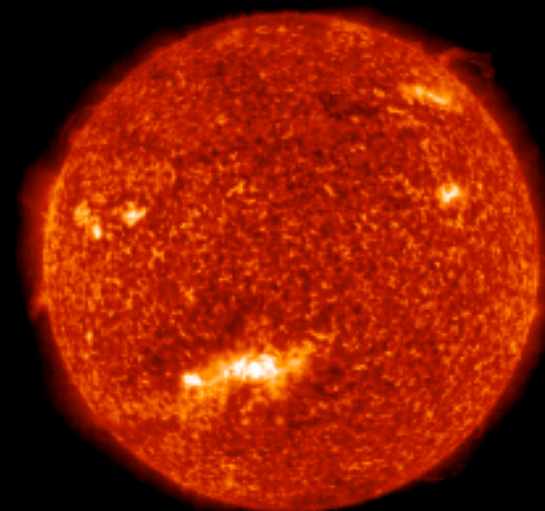
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195 Å



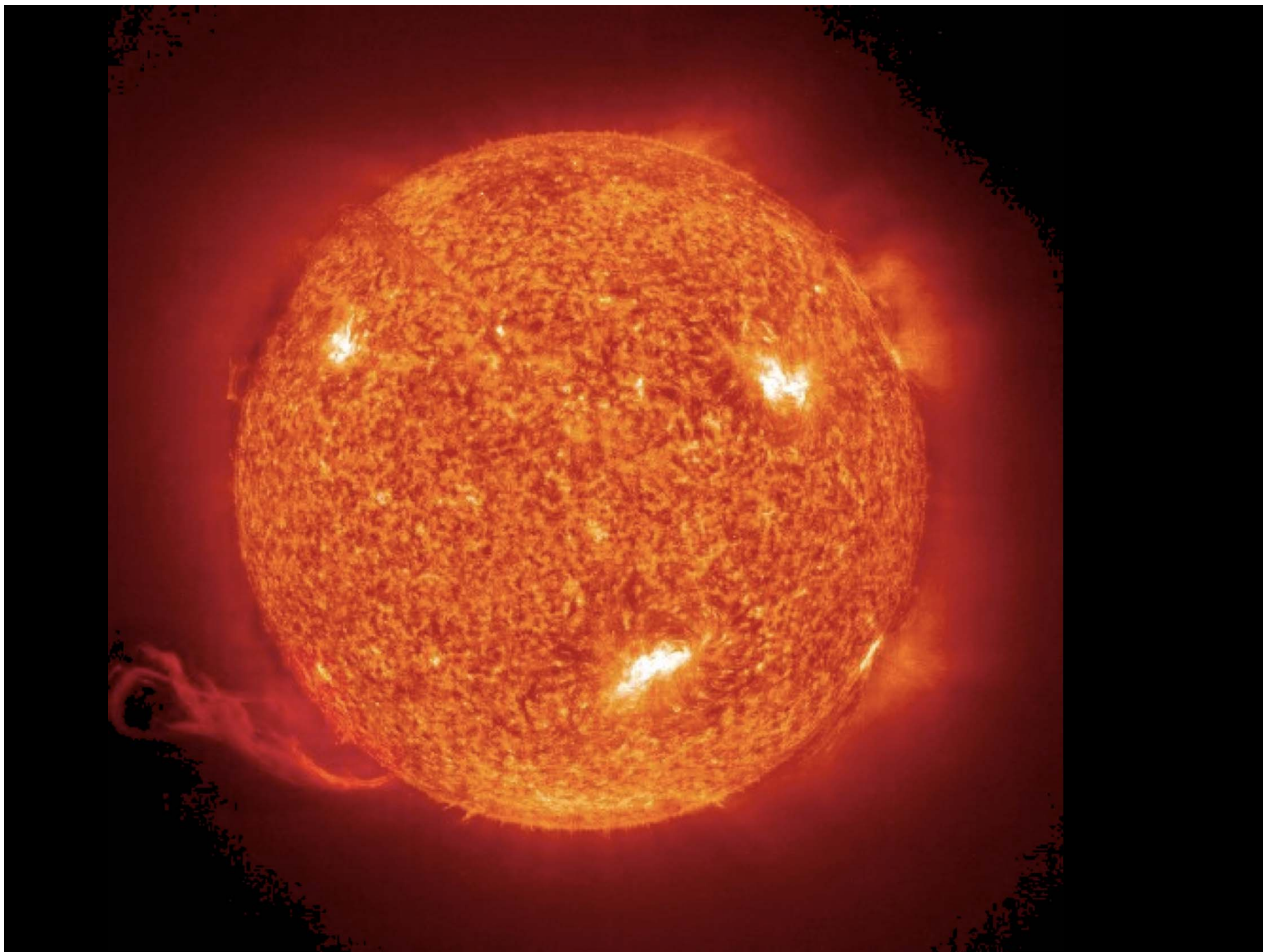
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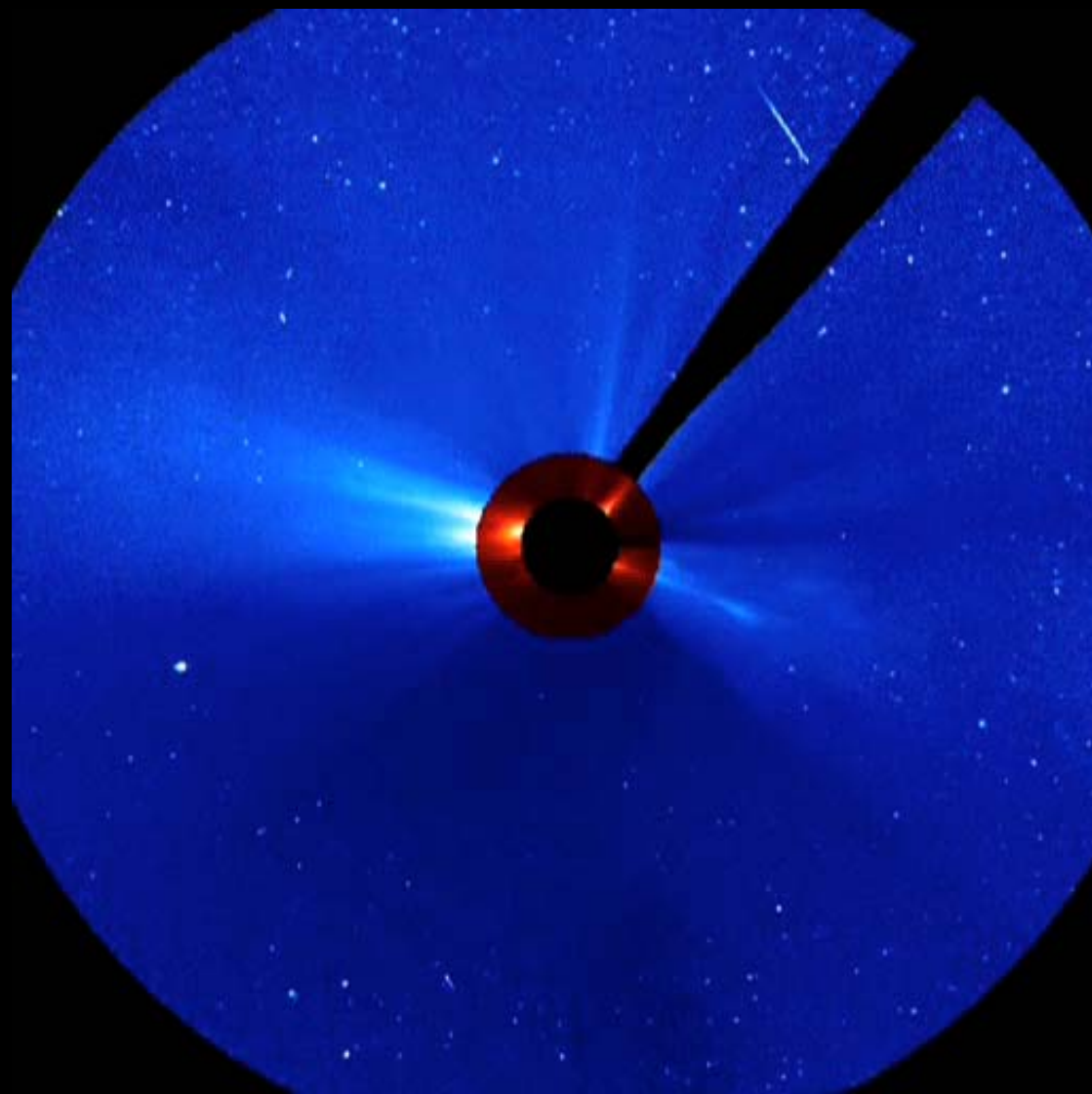
284 Å

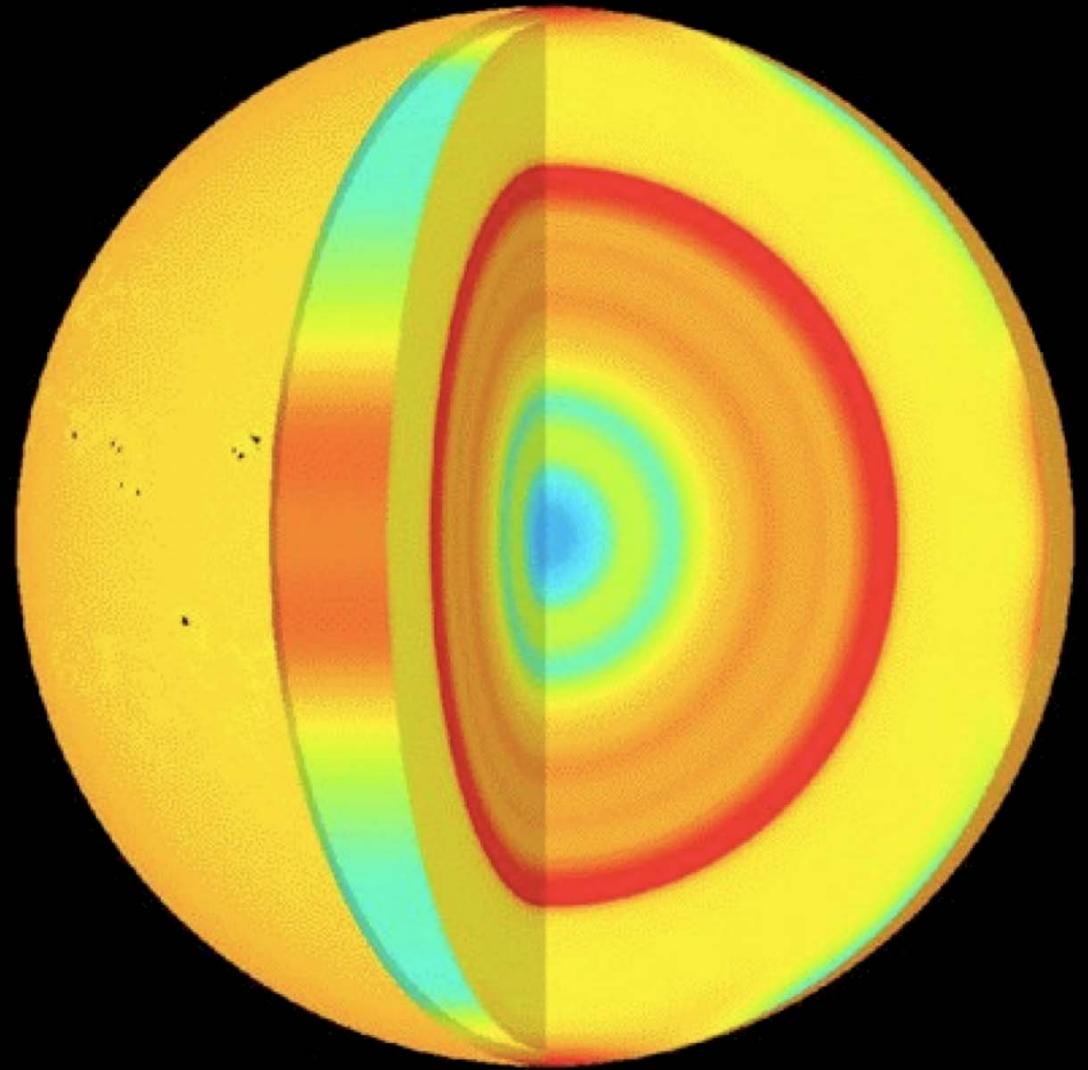


2010/11/10 01:19

304 Å





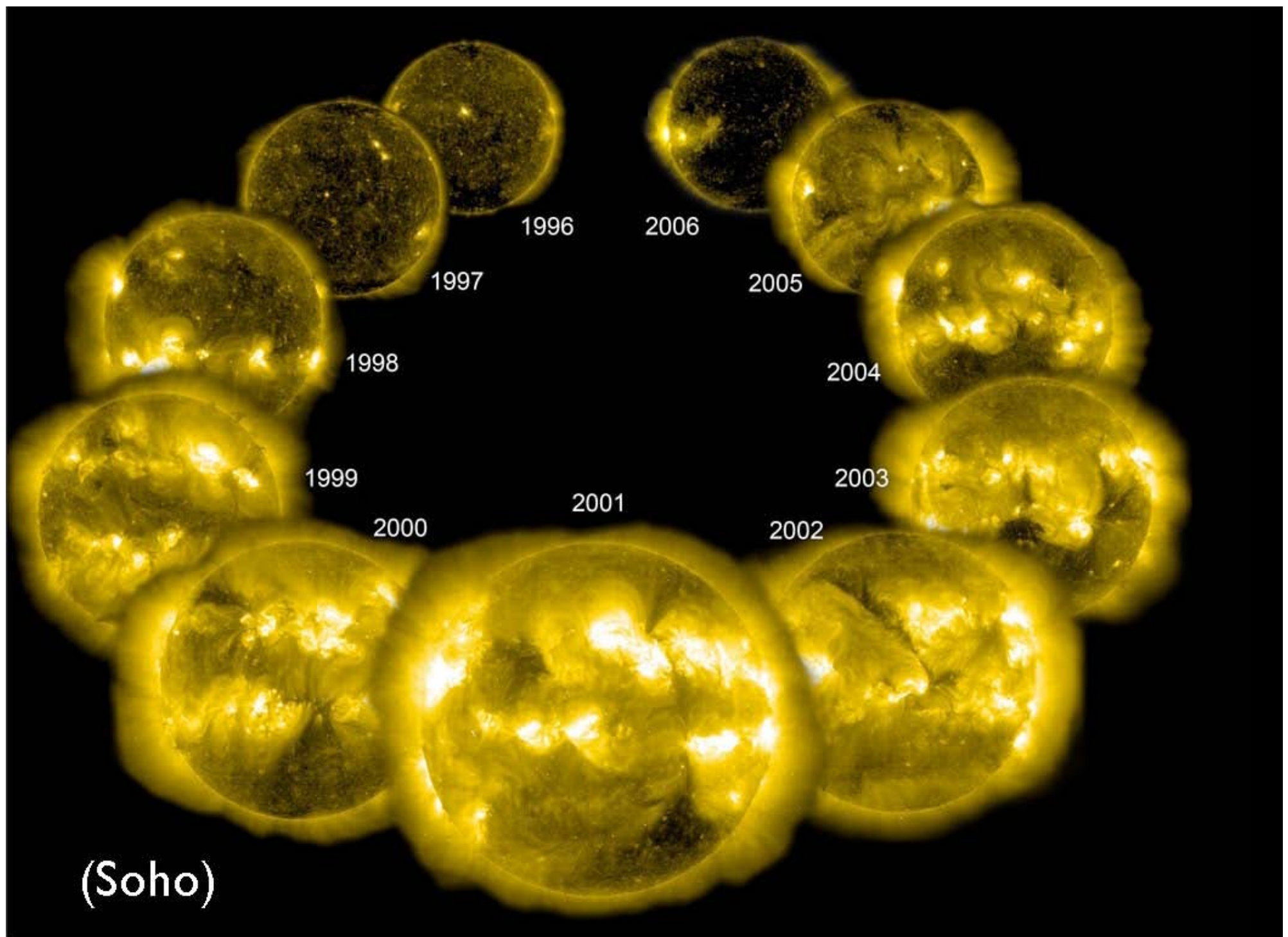


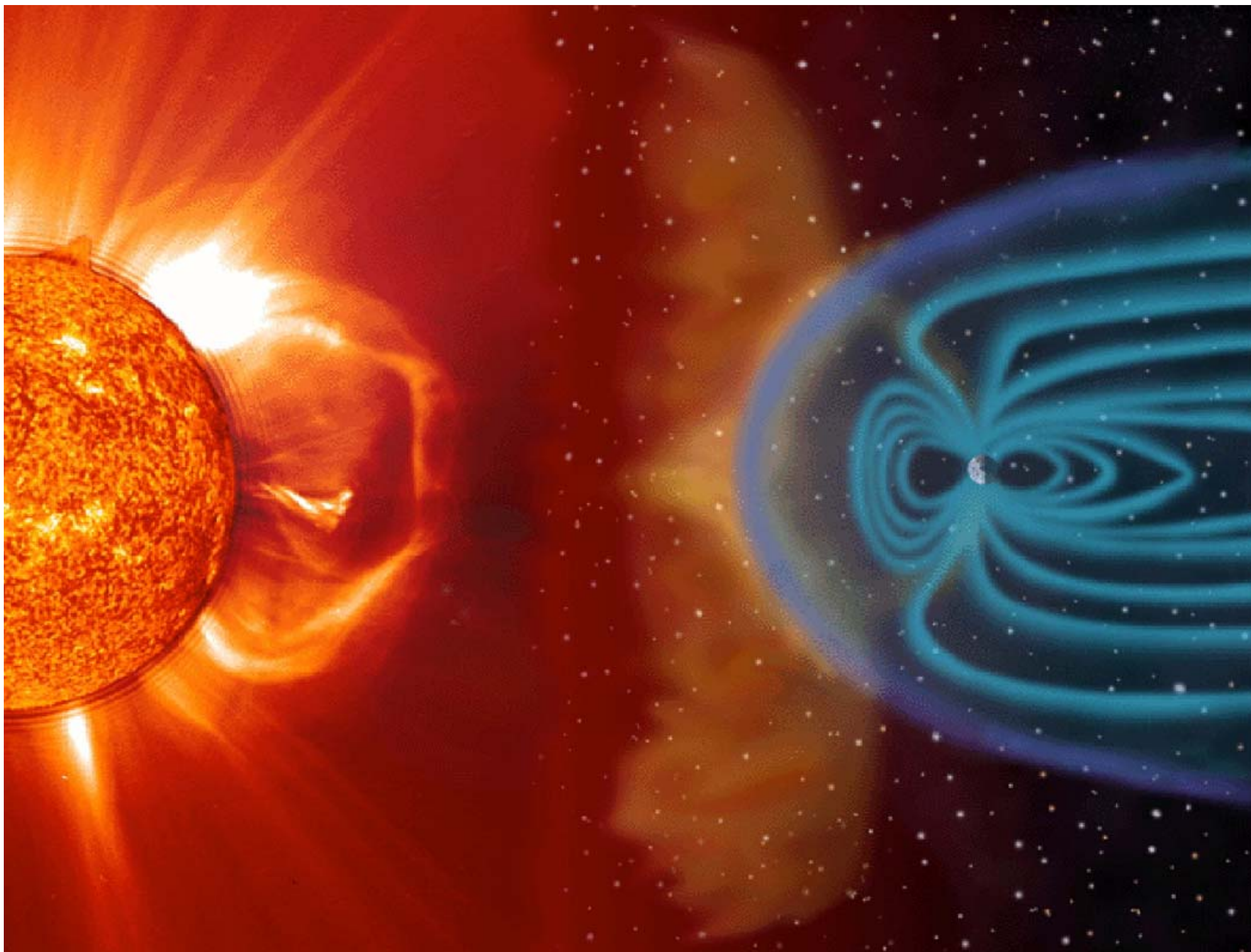
La rotazione all'interno del Sole.

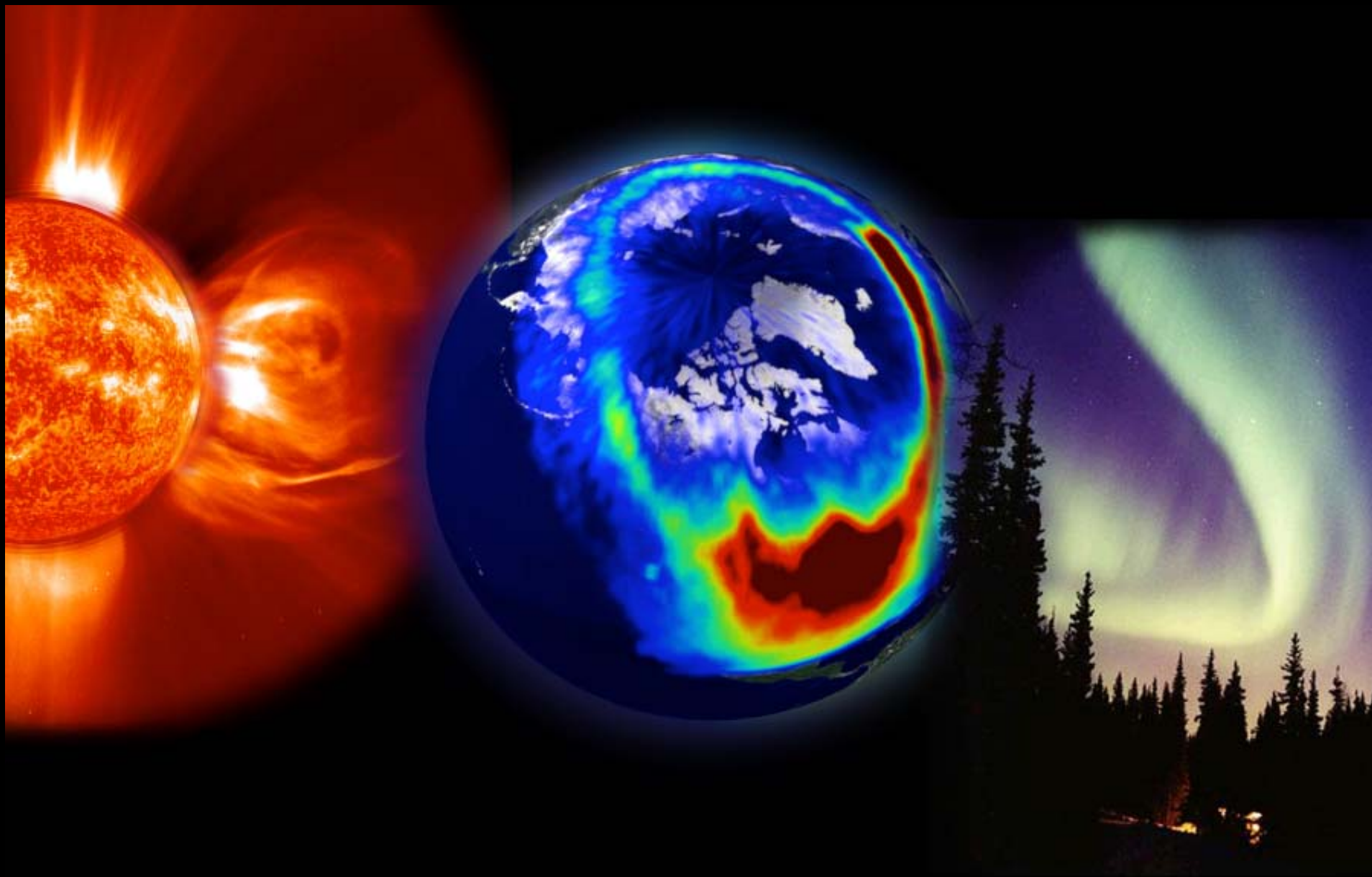
Rosso-Giallo: rotazione veloce

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









Le aurore polari

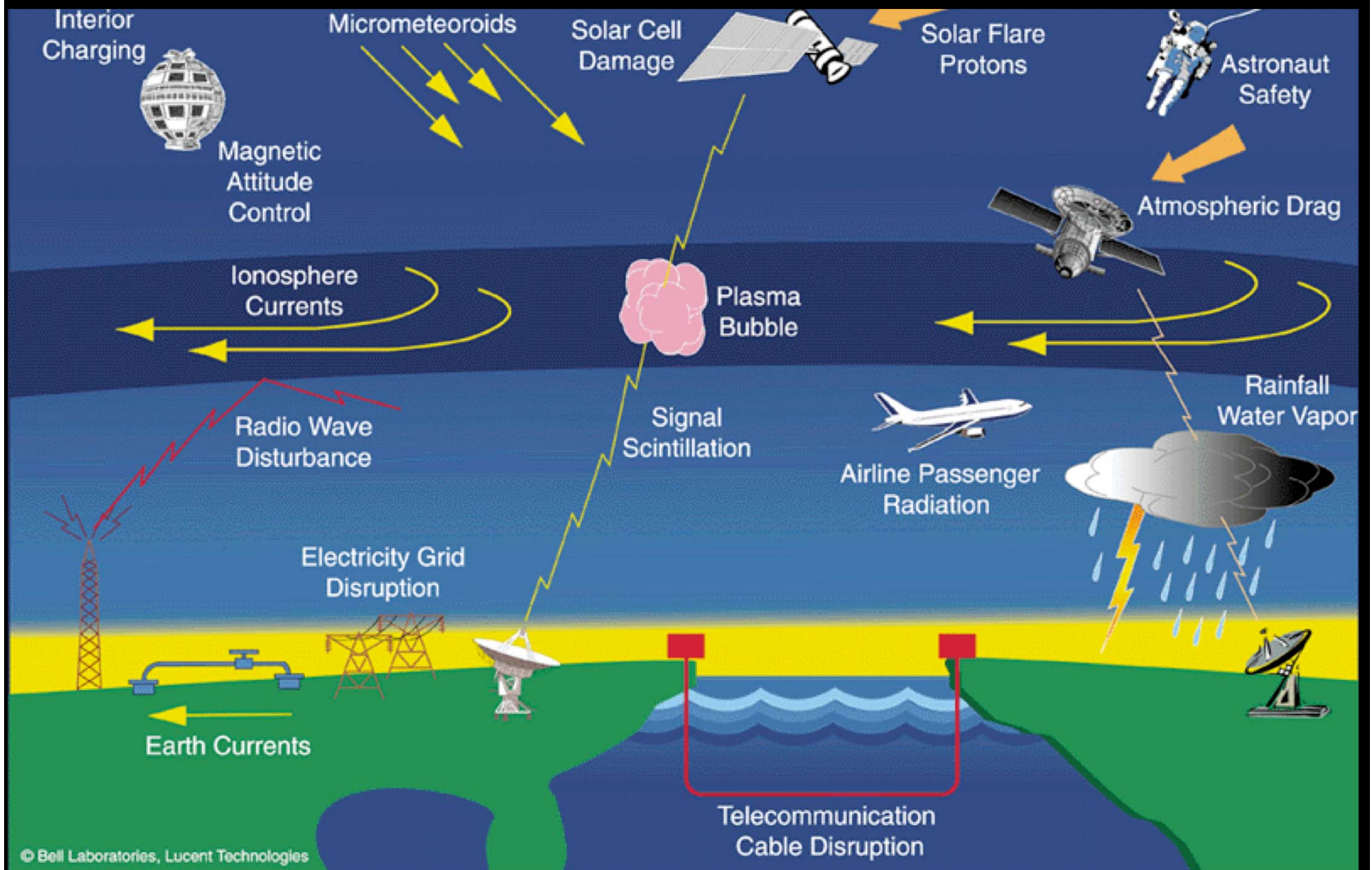
Wednesday 19 December 2012



Le aurore polari



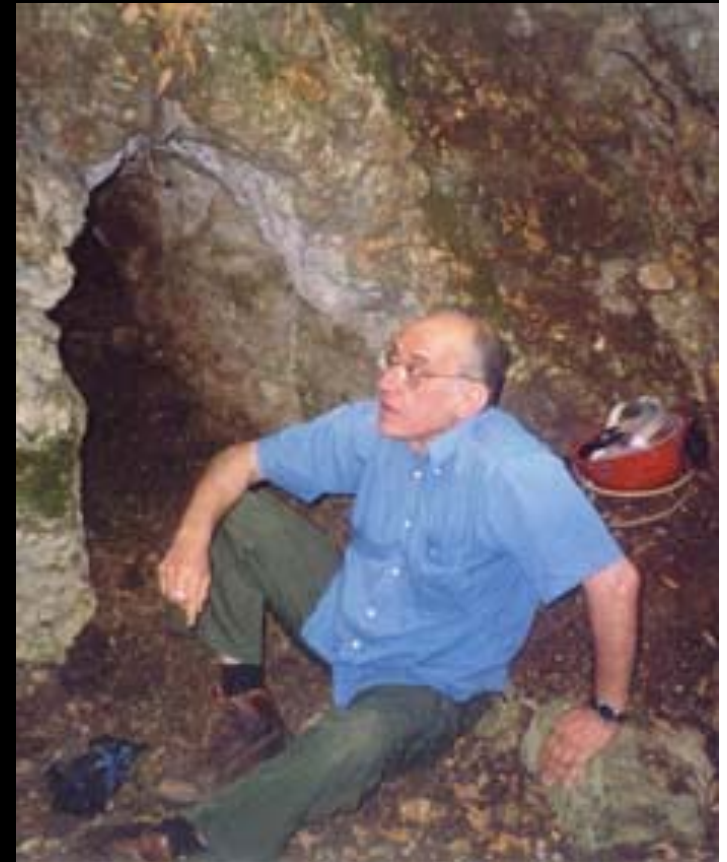
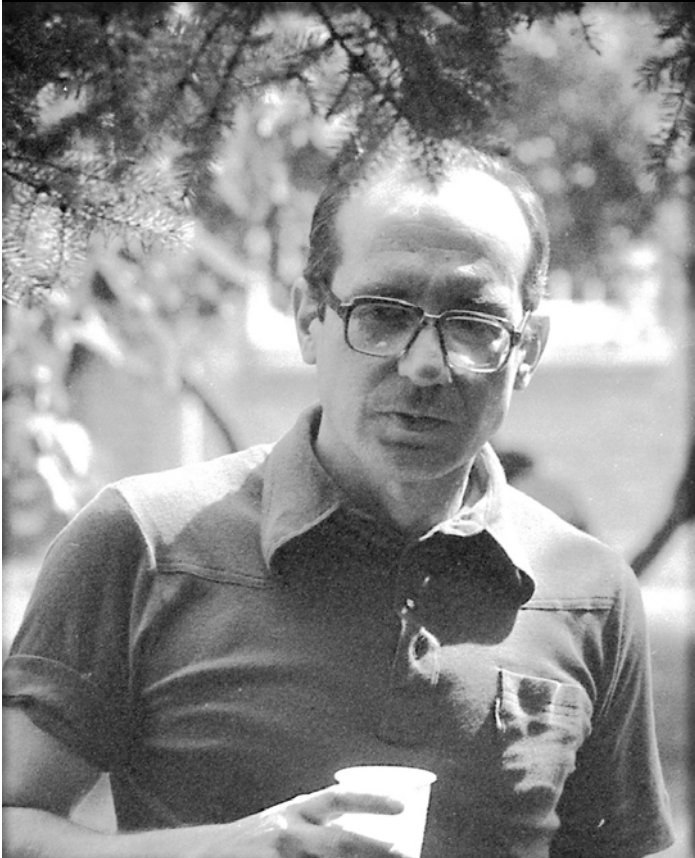
Quebec, 13 marzo 1989



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

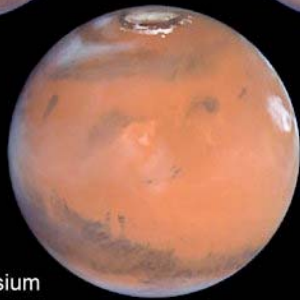
La forma delle cose



Acidalia



Tharsis



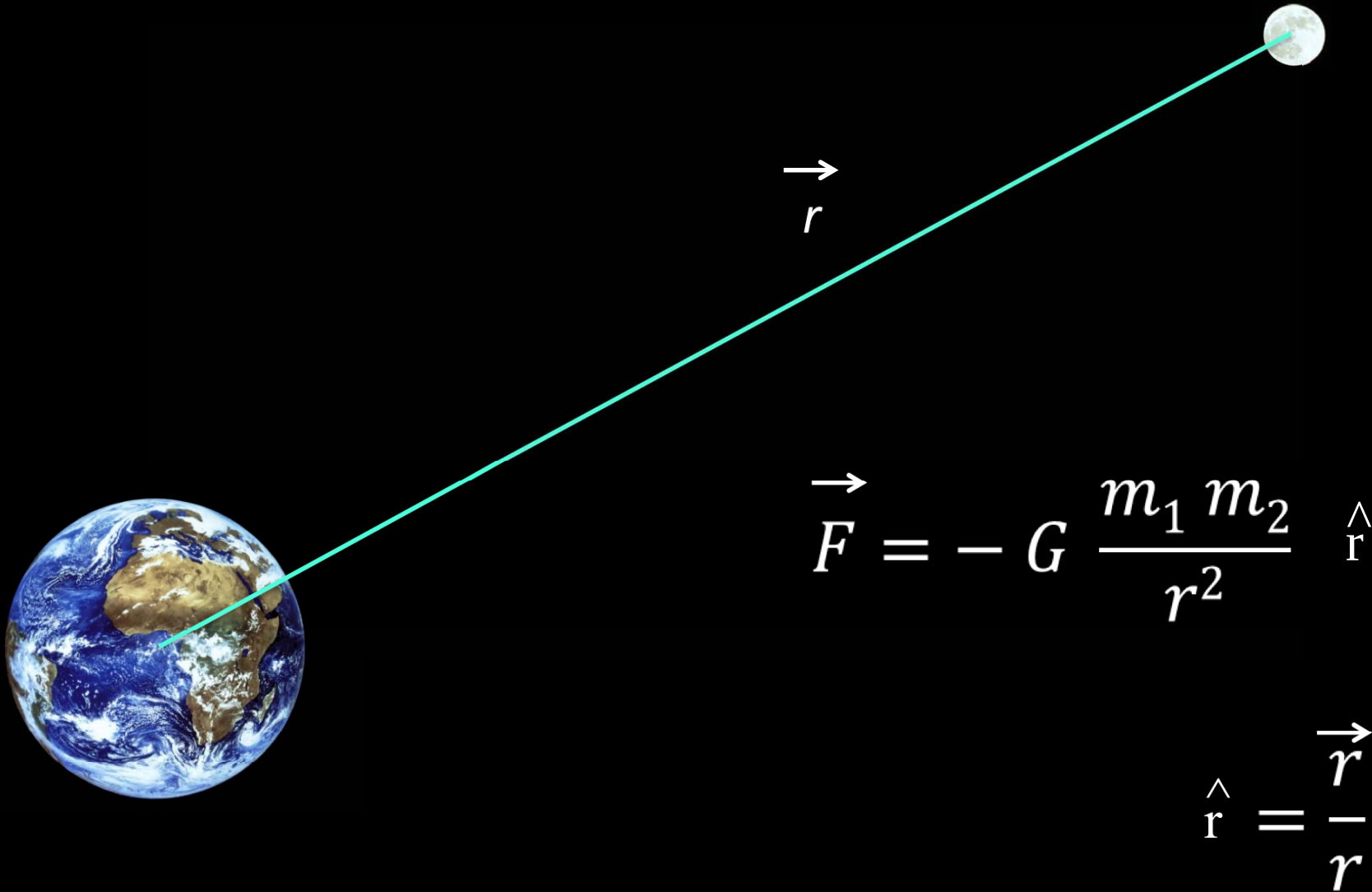
Elysium

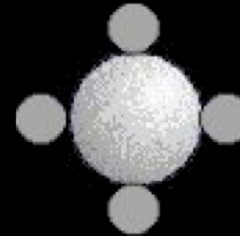
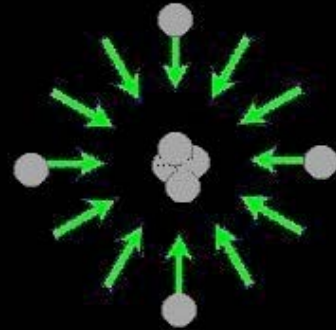
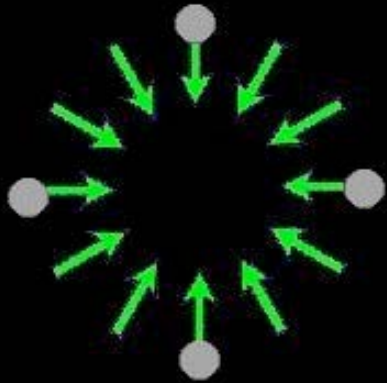


Syrtis Major

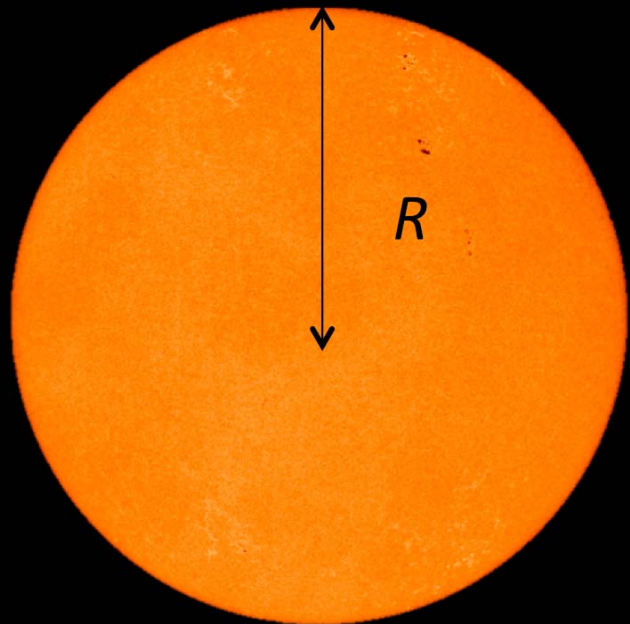


La legge di gravitazione





In assenza di rotazione
una forza centrale
costruisce oggetti sferici



0

j

N

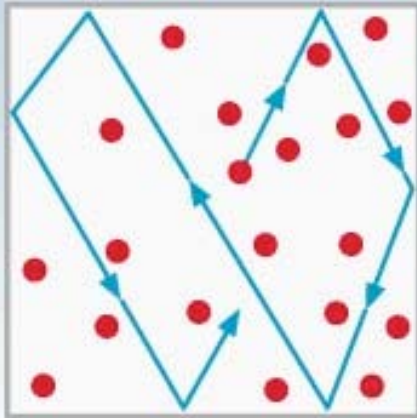
$j = 0, N$



Termodinamica

Il sole è una sfera di gas

gas perfetto

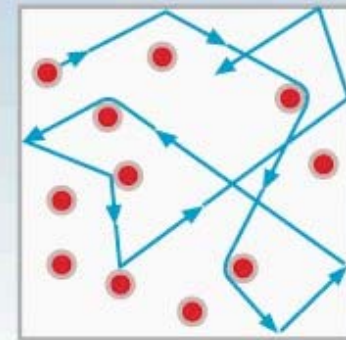


equazione di stato

$$P V = n R T$$

Le particelle **non** si urtano fra loro

gas reale



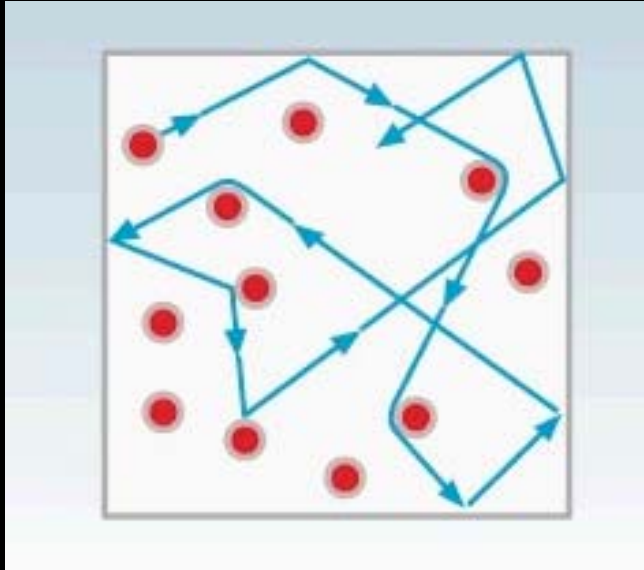
Le particelle si urtano fra loro:

interazione gravitazionale

interazione elettromagnetica

...

Sole: sfera di gas



gas reale

- elettroni
- ioni
- luce

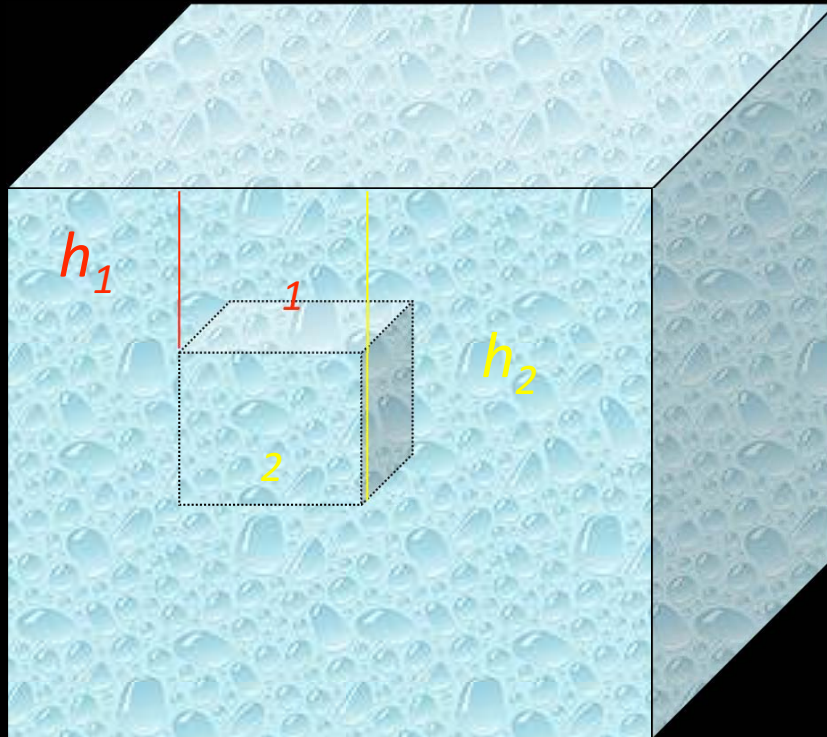
$$P = P_{gas} + P_{luce}$$

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

equazione di stato



Il sole è in equilibrio (idro)statico

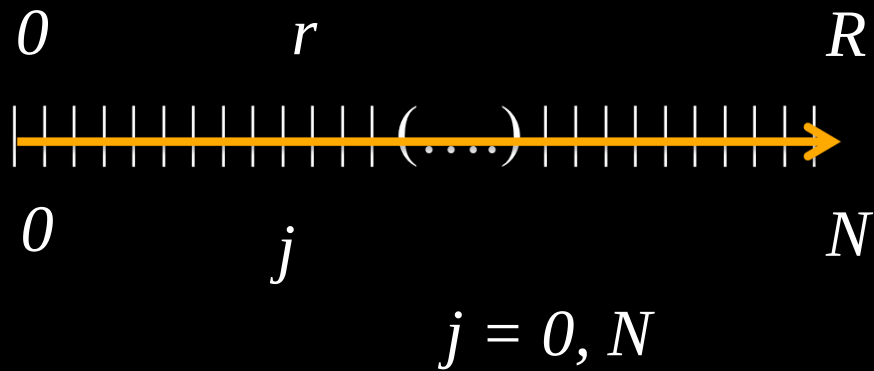


$$\sum_{i=0}^n \vec{F}_i = 0$$

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

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

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



variabile indipendente

Variabili dipendenti: P, T, ρ

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

Equilibrio idrostatico

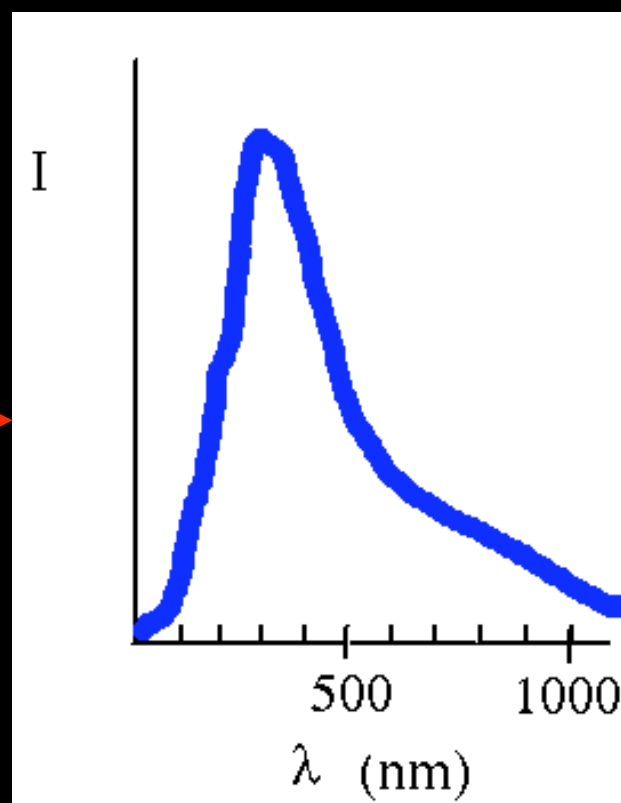
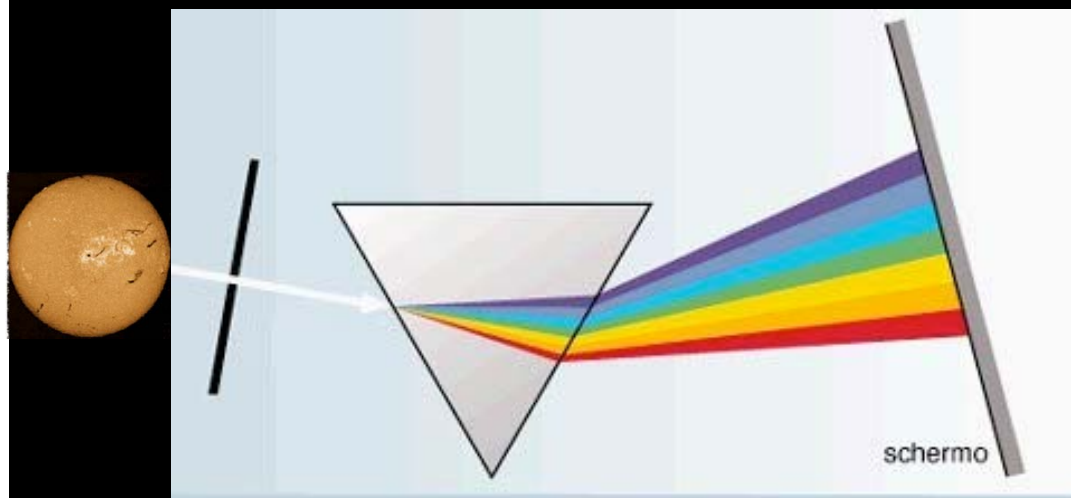
$$P_j = P_j(\rho_j, T_j)$$

Equazione di stato

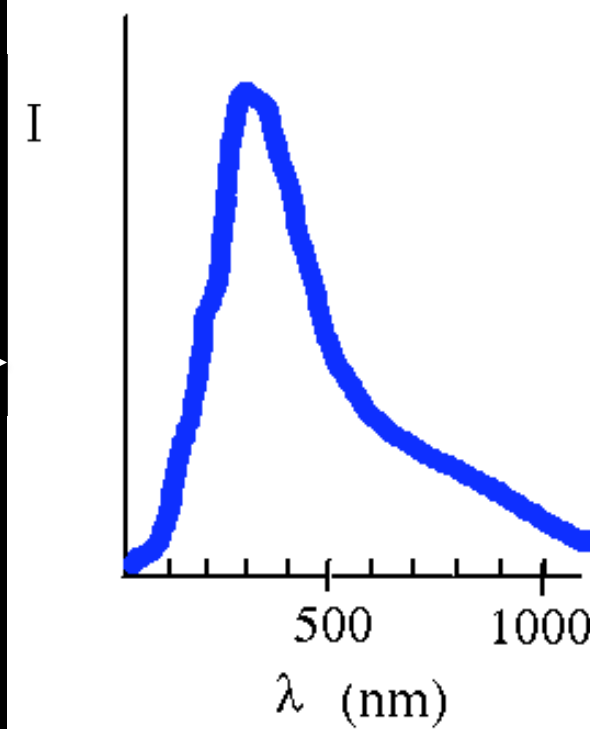
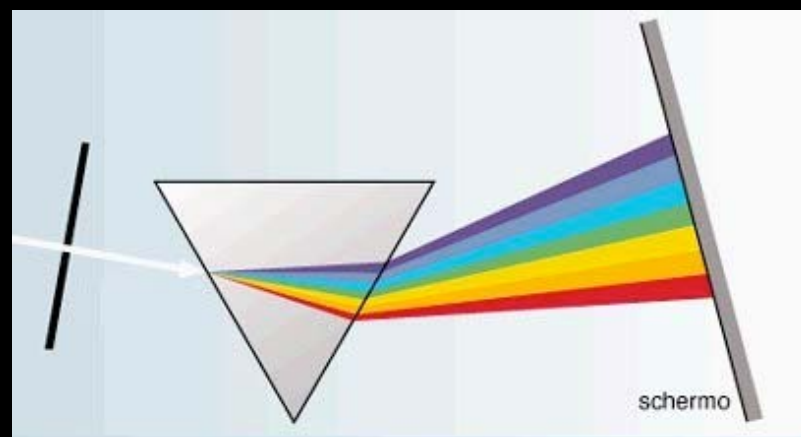
$$m_{j+1} - m_j = 4 \pi r_j^2 (r_{j+1} - r_j) \rho_j$$

Equazione di continuità

Il Sole come
“corpo nero”



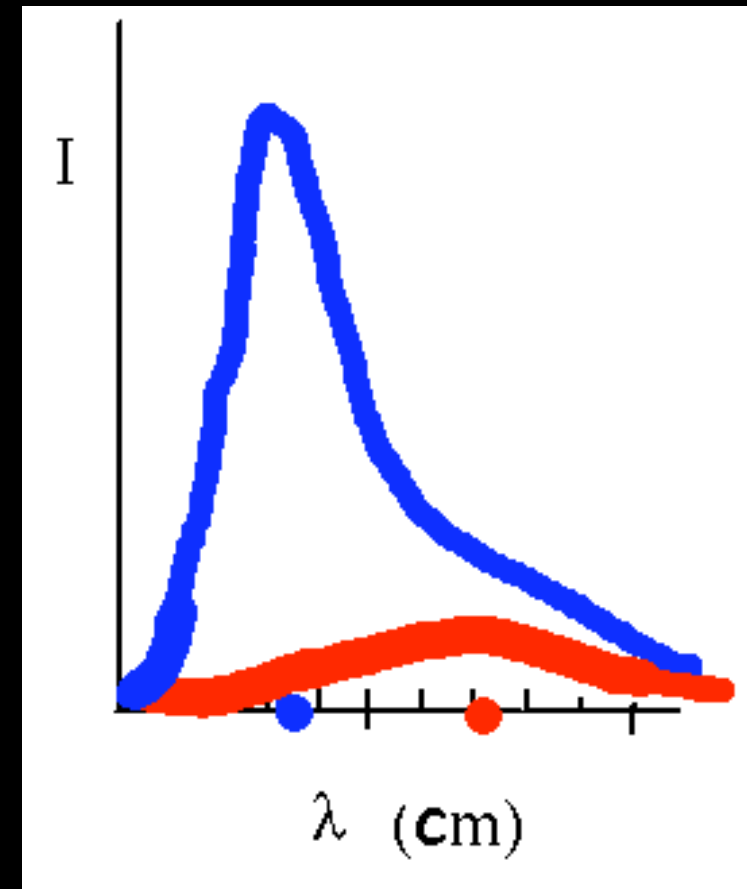
Sorgente
di
luce
bianca



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

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:

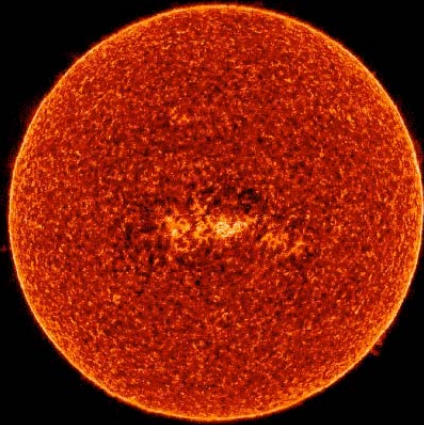
$$L_{sole} \approx 4 \times 10^{26} \text{ J / s} = 4 \times 10^{26} \text{ W}$$

Qual è la sorgente di questa energia?

Un fiammifero si consuma

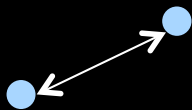


Ipotesi termodinamica



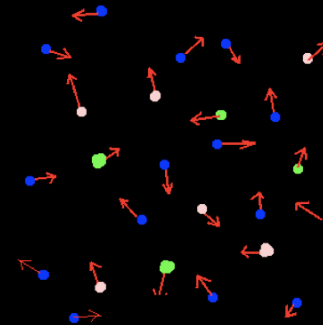
= gas in interazione gravitazionale

*Energia potenziale
gravitazionale*



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

Energia cinetica

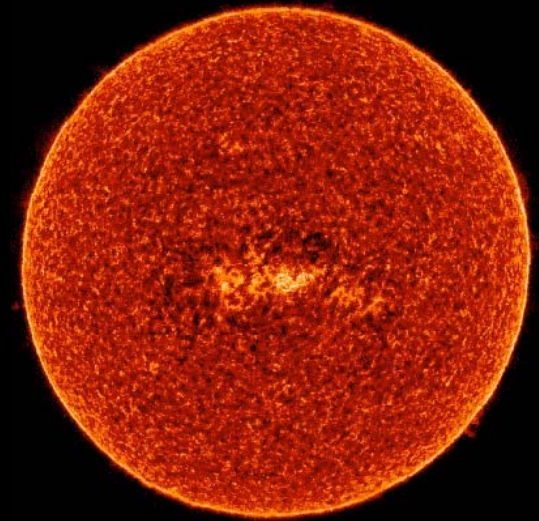


E_{cin}

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

Equilibrio

$$0 = 2 E_{cin} + U$$

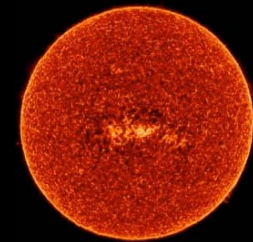


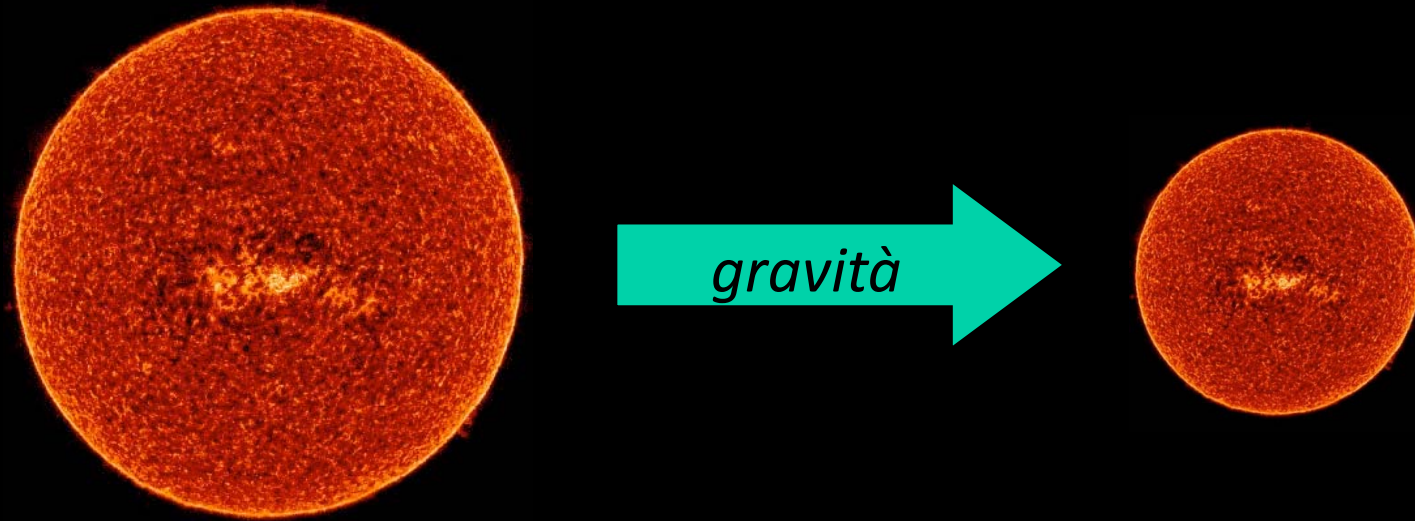
$$2 \Delta E_{cin} + \Delta U = 0$$

*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:

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

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,² 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:

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

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,³ 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 abundances⁴ it is necessary to assume the integral of ρdt 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 universe⁵ the density dependence on time is given by $\rho \propto 10^9/\beta$. 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:

$$\int_{t_0}^{\infty} (10^9/\beta) dt \leq 5 \times 10^4, \quad (2)$$

which gives us $t_0 \leq 20$ sec. and $\rho_0 \leq 2.5 \times 10^4$ 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 2.5×10^4 g sec./cm³ which can possibly be understood if we

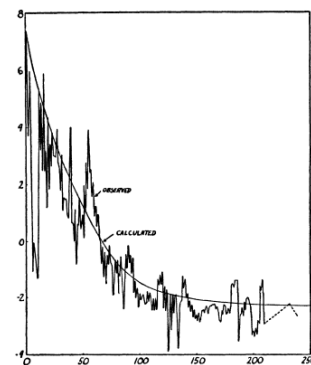


FIG. 1.
Log of relative abundance
Atomic weight

1957

REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4

OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBRIDGE, G. R. BURBRIDGE, 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)

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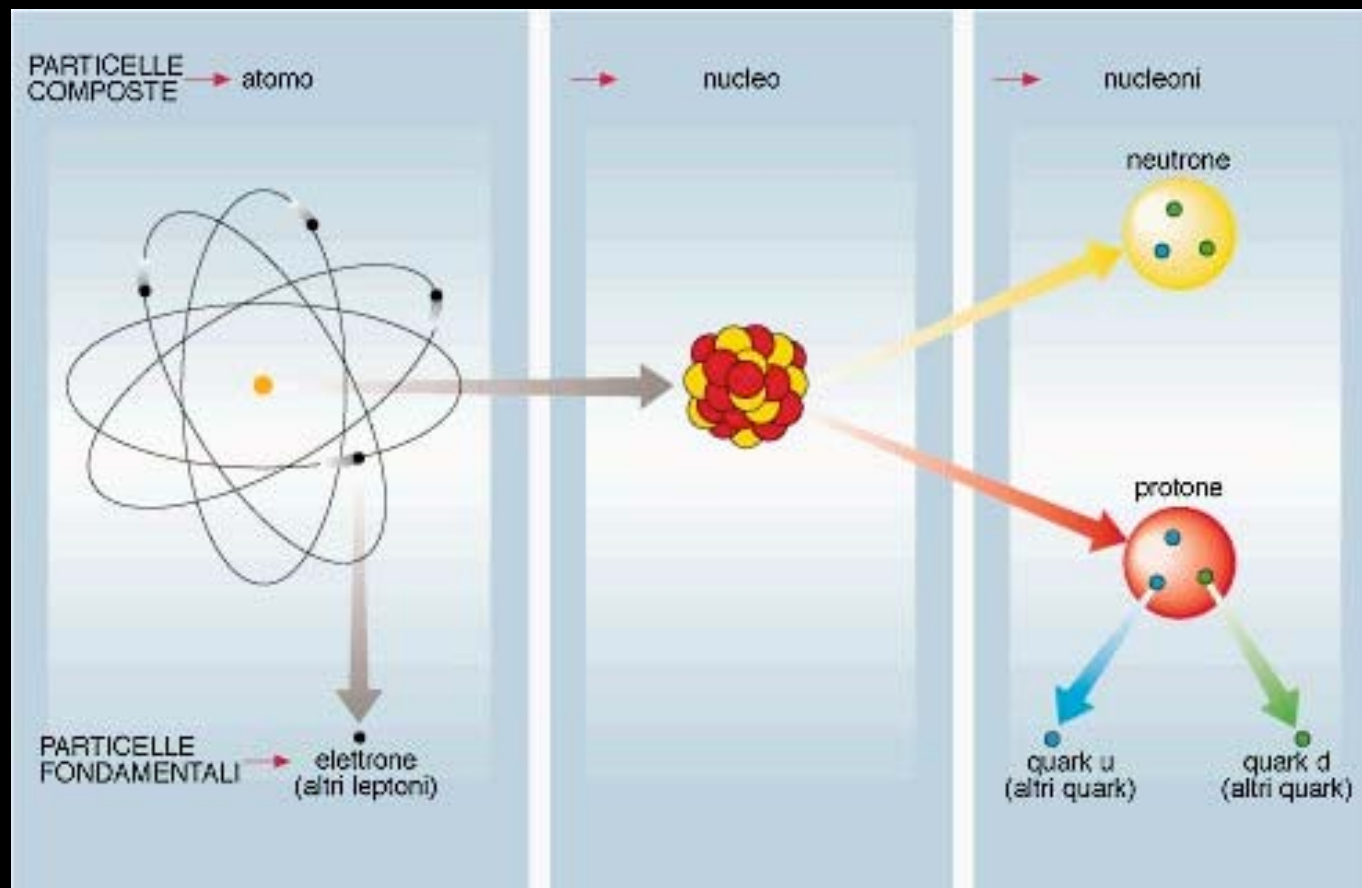
* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

Viaggio all'interno del Sole



www.spacetelescope.org

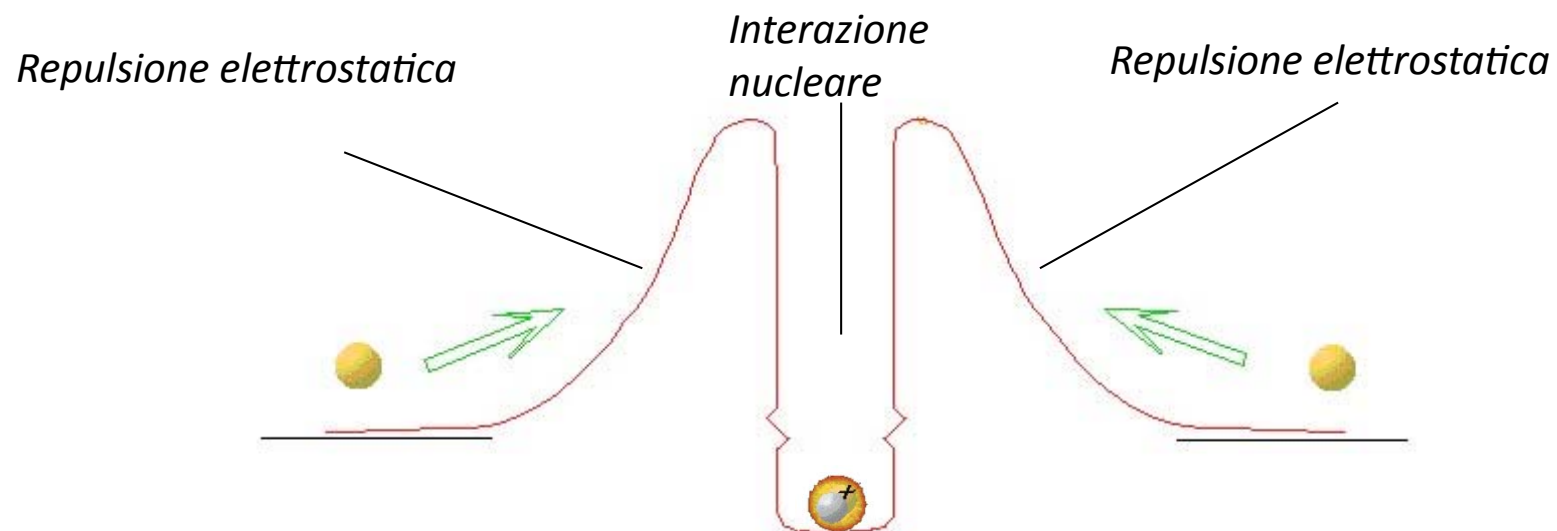
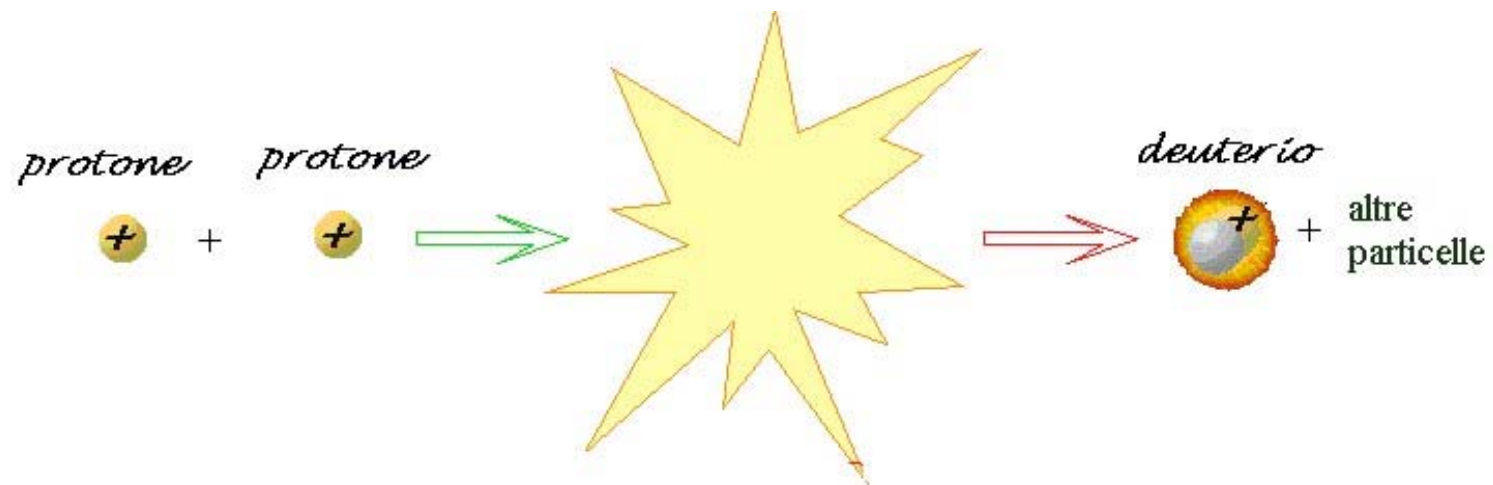
Le reazioni nucleari



La catena protone protone



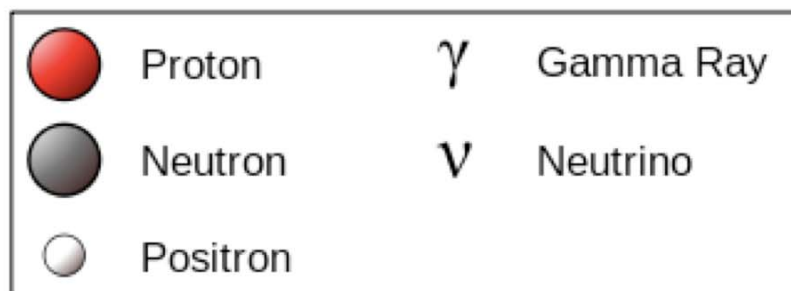
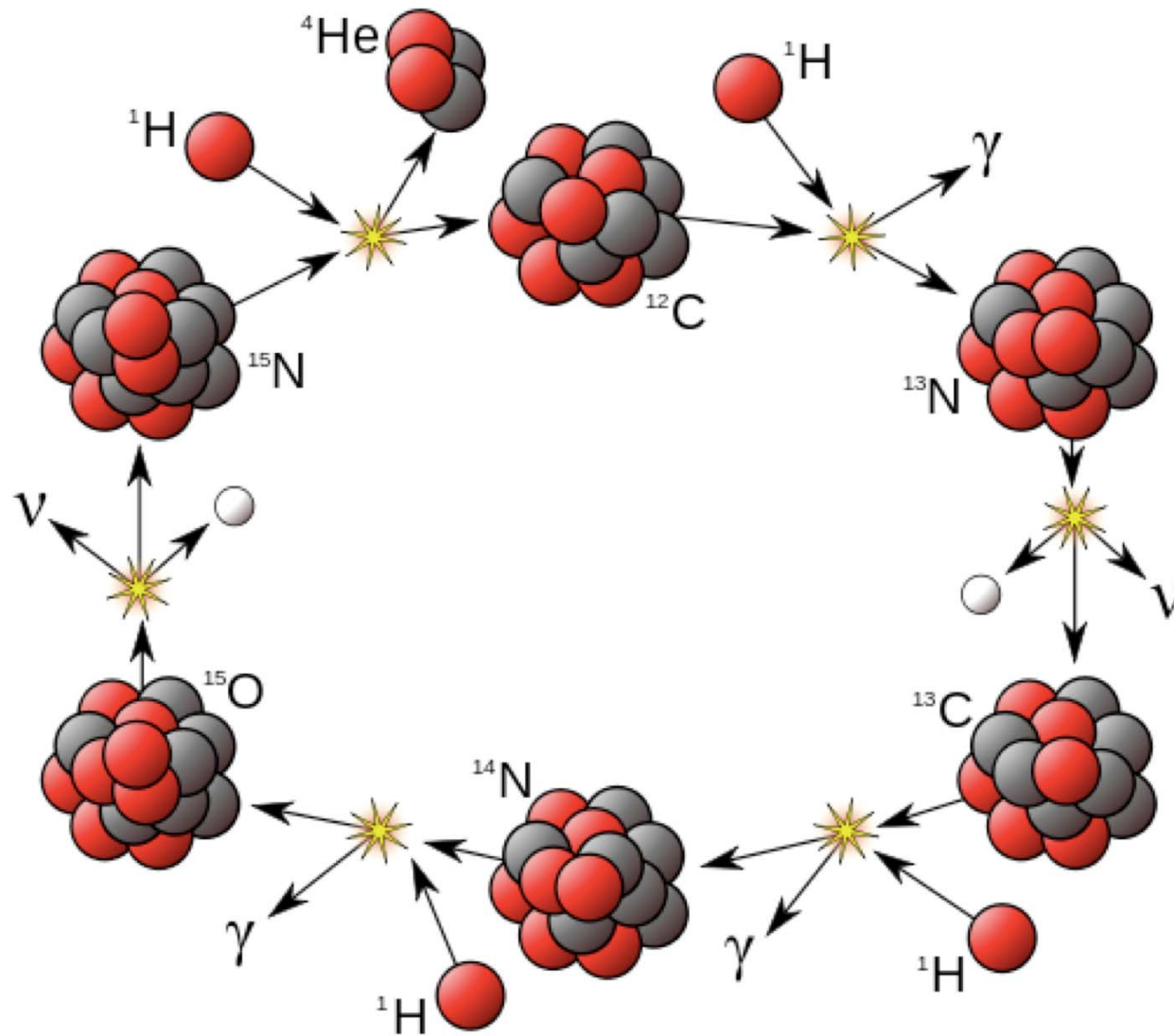
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La catena protone protone



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Massa di 1 protone

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

Massa di 1 neutrone

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

Massa di 2 protoni + 2 neutroni

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

Massa di 1 nucleo di Elio (He)

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

Perché questa differenza? Energia di legame

Nella catena p-p,



Massa di 4 atomi di idrogeno (4H)
 $= 6,690 \times 10^{-27} \text{ Kg}$

Massa di 1 atomo di Elio (He)
 $= 6,646 \times 10^{-27} \text{ Kg}$

Differenza di Massa

$= (\text{massa 4 atomi di H}) - (\text{massa 1 atomo di He})$

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

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

Quindi: ENERGIA LIBERATA nella FUSIONE

$$= (\text{Differenza di Massa}) \times c^2$$

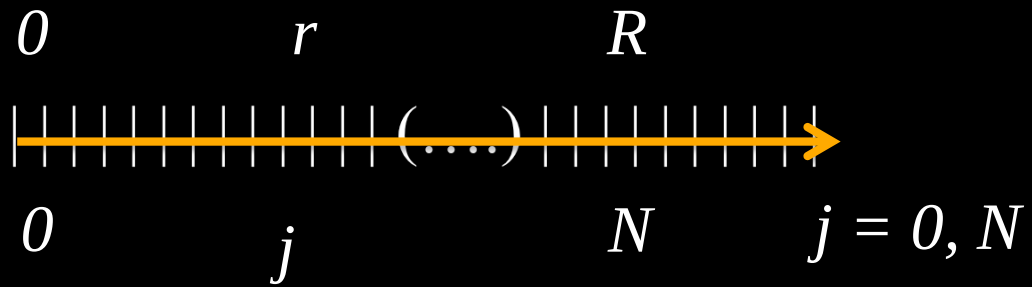
$$= 4.22 \times 10^{-12} \text{ Joule}$$

energia liberata per un grammo di materia

$$= 6.30 \times 10^{11} \text{ Joule}$$

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

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



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

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

conservazione energia

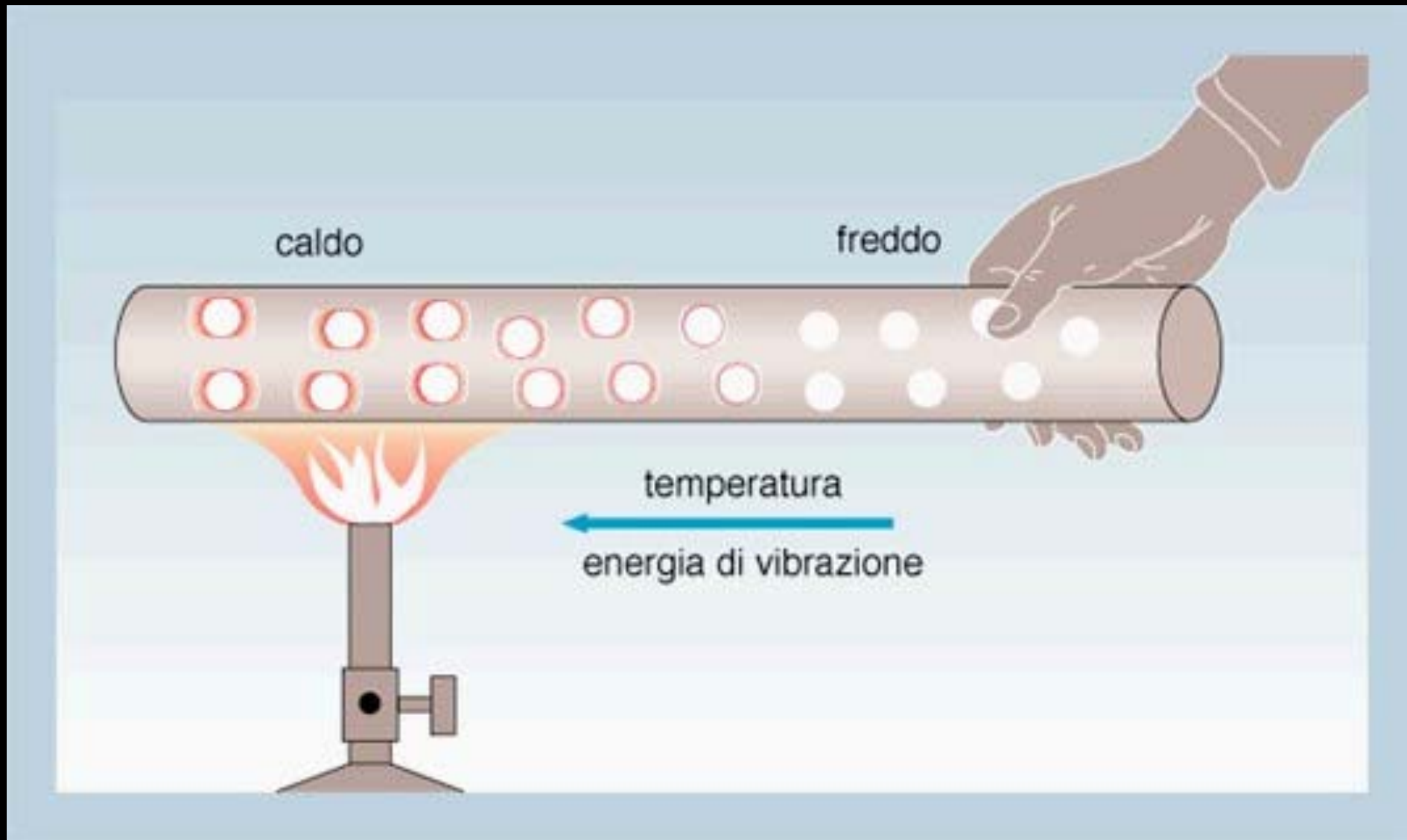
$$\kappa_j = \kappa_j(\rho_j, T_j)$$

Trasporto di energia

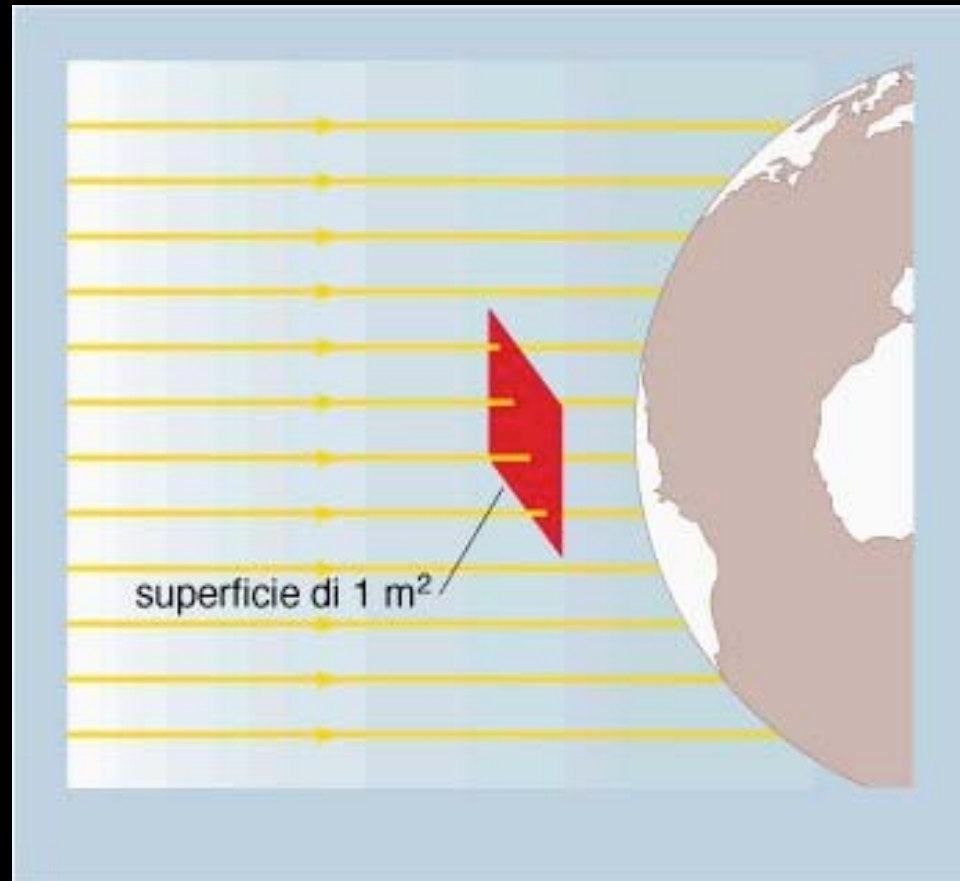
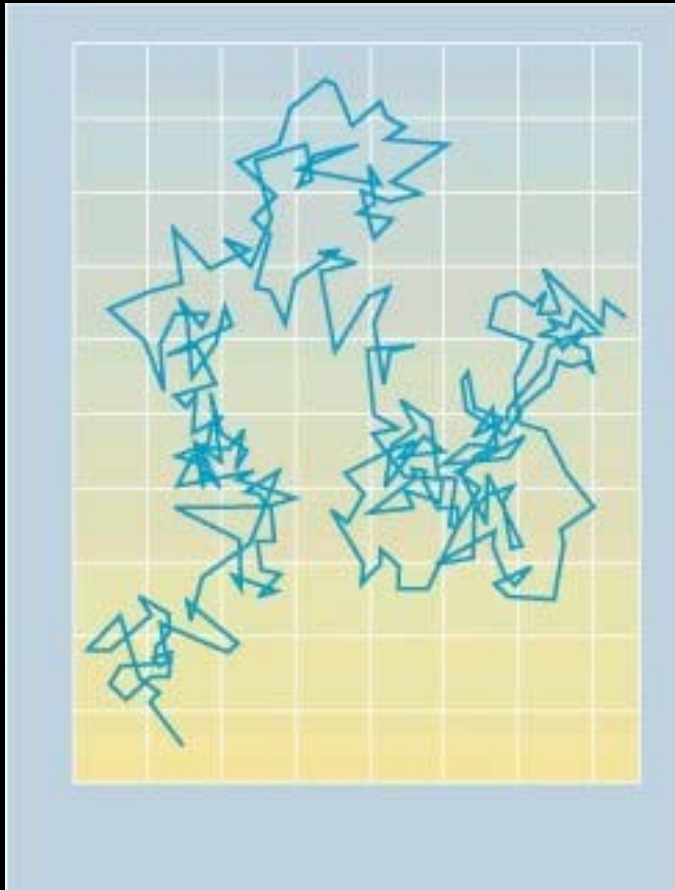
$$T_{j+1} - T_j = \dots$$

equazione del trasporto

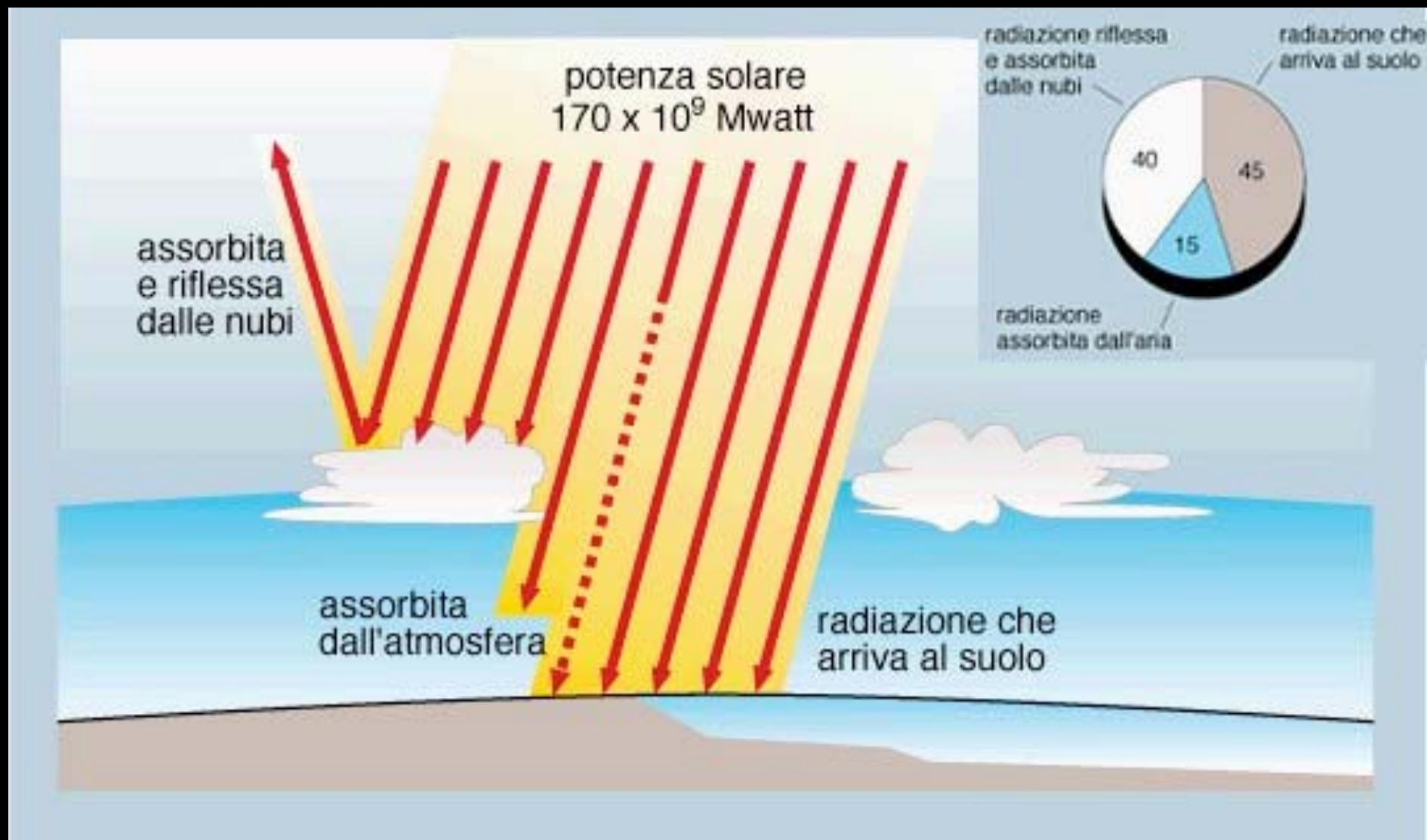
Trasporto energia 1: la conduzione



Trasporto energia 2: l'irraggiamento



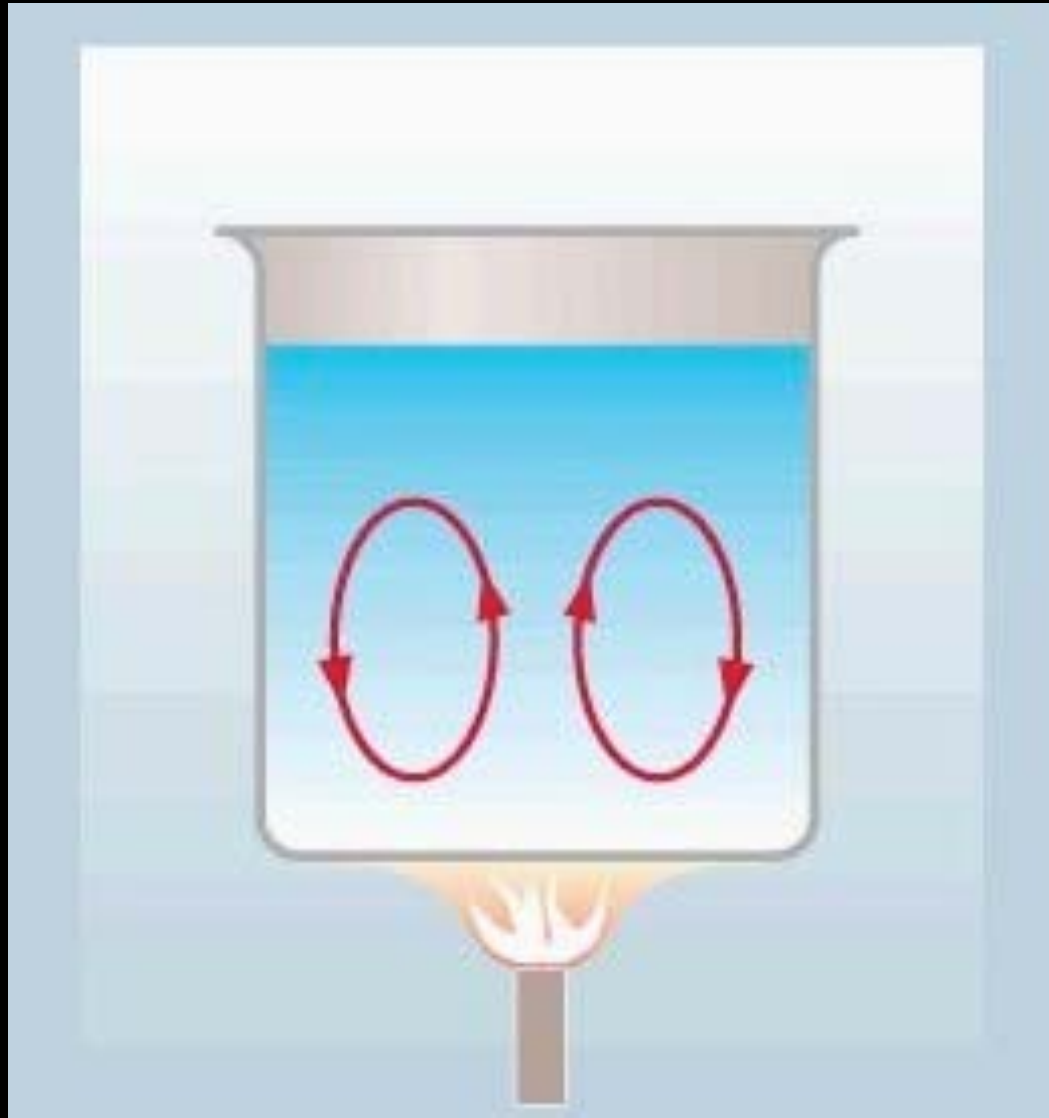
Trasporto energia 2: l'irraggiamento



Trasporto energia 3: la convezione



Trasporto energia 3: la convezione



Trasporto energia: sintesi

Conduzione

solo nei solidi

Irraggiamento

meccanismo principale

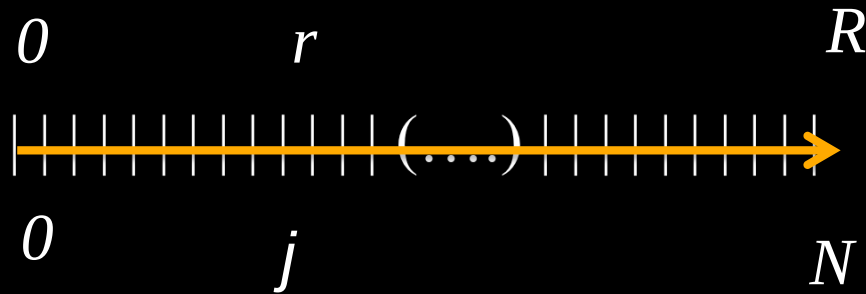
Convezione

meccanismo di «troppo pieno»

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

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

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

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

