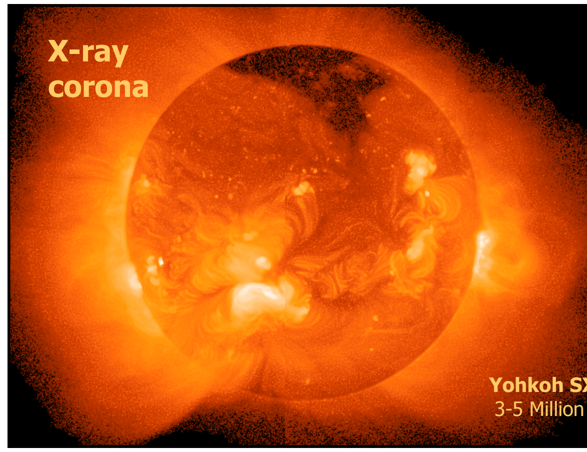
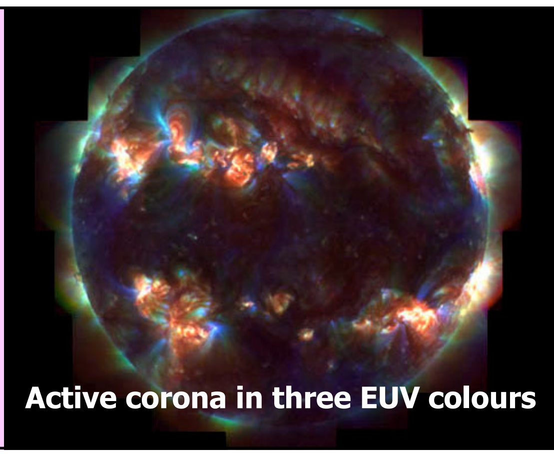
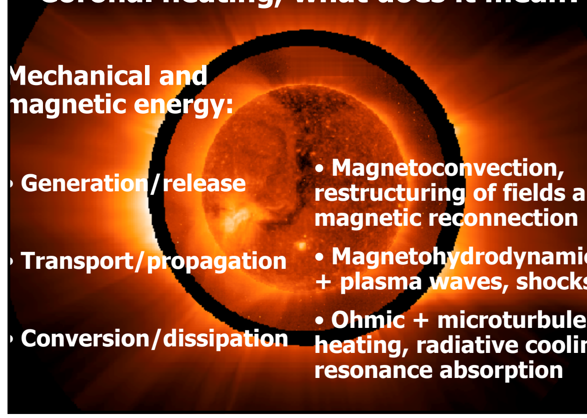
Coronal heating and energetics

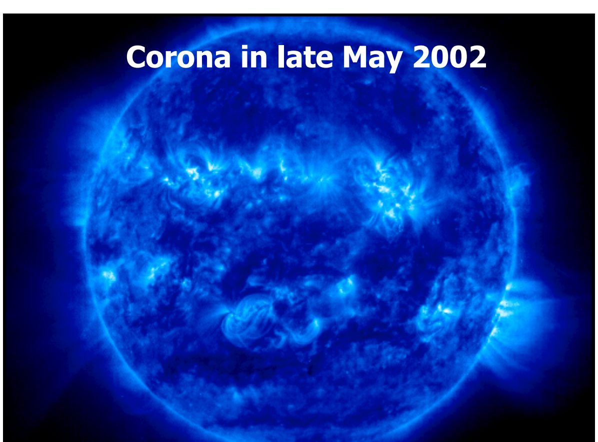
- Global structure of the solar corona
- Coronal heating, what does it mean?
- Dissipation processes in the corona
- Observations of MHD waves in loops
- Dynamics of the magnetic network
- Flares and coronal heating





Coronal heating, what does it mean?





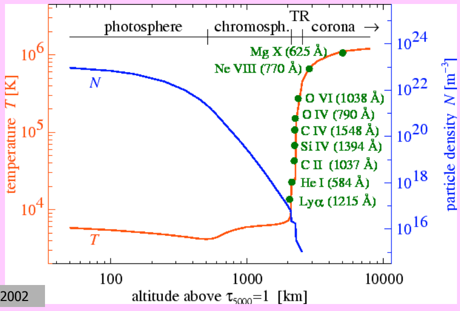
Energetics of the solar corona

Parameter (erg $cm^{-2}s^{-1}$)	Coronal hole (open)	Active region (closed)
Chromospheric radiation loss	4 10^6	2 10^7
Radiation	10^4	< 10^6
Conduction	5 10^4	10^5 – 10^6
Solar wind	(5-10) 10^5	(< 10^5)

Photosphere: 6.3 10^{10} erg cm^{-2} s^{-1}

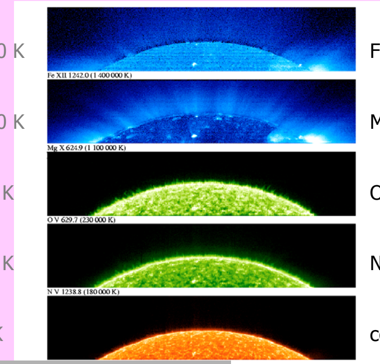
10^5 erg cm^{-2} s^{-1} = 100 W m^{-2}

Multiply ionized atoms indicate temperature gradient



Peter, 2002

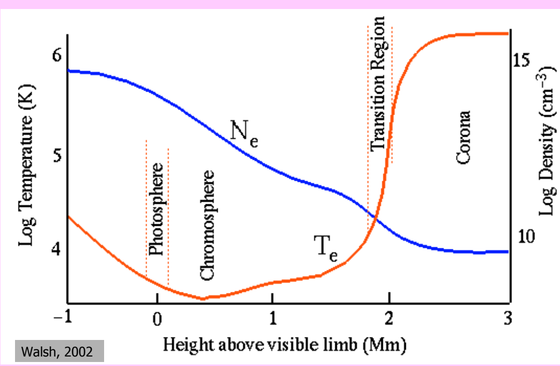
North coronal hole in various lines



Forsyth & Marsch, Space Sci. Rev., **89**, 7, 1999

SUMER/SOHO 10 August 1996

How is the solar corona heated?



Walsh, 2002

Collisional heating rates

Chromosphere: $N = 10^{10}$ cm^{-3} h_G = 400 km
Perturbation scales: ΔL = 200 km, ΔB = 1 G, ΔV = 1 km/s, ΔT = 1000 K

Viscosity: $H_V = \eta\,(\Delta V/\Delta L)^2 = 2\ 10^{-8}$

Conduction: $H_C = \kappa\,\Delta T/(\Delta L)^2 = 3\ 10^{-7}$

Joule: $H_J = j^2/\sigma = (c/4\pi)^2(\Delta B/\Delta L)^2/\sigma = 7\ 10^{-7}$

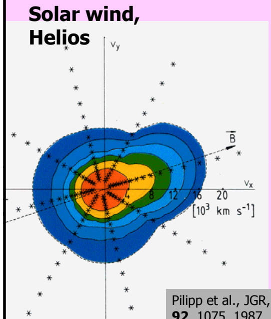
Radiative cooling: $C_R = N^2\Lambda(T) = 10^{-1}$ erg cm^{-3} s^{-1}

Smaller scale, $\Delta L \approx 200$ m, required

$\lambda_{Coll} \approx 1$ km

Electrons and Coulomb collisions

Solar wind, Helios



Pilipp et al., JGR, **92**, 1075, 1987

Parameter	Chromo -sphere	Corona ($1.3R_S$)	Solar wind (1AU)
n_e /cm^{-3}	10^{10}	10^7	10
T_e /K	$2\ 10^3$	$1\text{-}2\ 10^6$	10^5
λ /km	1	1000	10^7

- **Non-Maxwellian**
- **Heat flux tail**
- **Temperature anisotropy**

Perpendicular filamentary structure in fine loops and coronal emission

1. Filamentary nature of loops is consequence of fine solar fields....
2. Transient localised heating with threshold.....
3. Non-classical diffusive perpendicular transport by turbulence too slow....
4. Field line stochasticity?

- Relative rarity of loops, high contrast
- Well-defined transverse dimension

Litwin & Rosner, ApJ **412**, 375, 1993

Requirements on coronal transport

Coronal plasma beta is low, $\beta \approx 0.1$ - 001, --> strongly magnetized particles, which move „freely" parallel to **B**.

Coulomb collisional transport, then diffusion coefficient:

$D_c = (\rho_e)^2 \nu_e \approx$ **1 m²s⁻¹**

with electron Larmor radius, $\rho_e \approx$ 25 cm, and collision frequency, $\nu_e \approx 10\ s^{-1}$; $\rho_p \approx$ 10 m, $B \approx 1$ G, $n_e \approx 10^8\ cm^{-3}$.

Enhanced transport only by „anomalous" processes: Waves, turbulence, drifts, flows, stochastic fields, hyperresistivity.....

Litwin & Rosner, ApJ **412**, 375, 1993

Loop switch-on time: $\tau \approx$ 1-10 s. Is the current channel scale comparable to transverse loop dimension, $a \approx$ 1000 km? Cross diffusion time: $t_D = a^2/D \approx 10^{12}$ s.

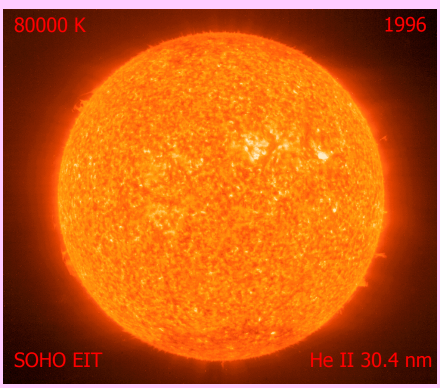
Coronal heating - an unsolved problem

Why?

Incomplete and insufficient diagnostics:

- **Only remote-sensing through photons (X-rays, extreme ultraviolet (EUV), visible, infrared) and electromagnetic waves (radio, plasma), and corpuscular radiation (solar wind, energetic particles)**
- **No coronal in-situ measurements, such as possible in other solar system plasmas (Earth's magnetosphere, solar wind,.......)**

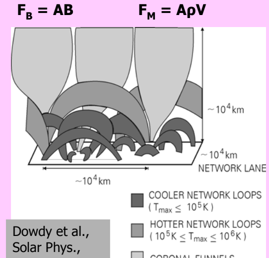
Corona and magnetic network



Magnetic network loops and funnels

Structure of transition region

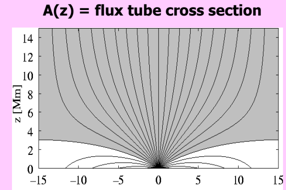
$F_B = AB$ $F_M = A\rho V$



Dowdy et al., Solar Phys., **105**, 35, 1986

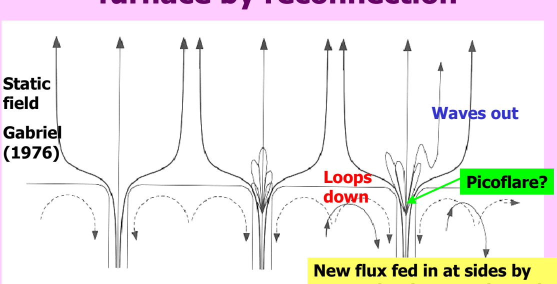
Magnetic field of coronal funnel

A(z) = flux tube cross section



Hackenberg, Marsch and Mann, Space Sci. Rev., **87**, 207, 1999

Dynamic network and magnetic furnace by reconnection



New flux fed in at sides by convection (t ~ 20 minutes)

$F_E = 10^7$ erg cm⁻² s⁻¹

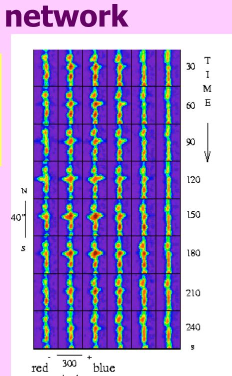
Axford and McKenzie, 1992, and Space Science Reviews, **87**, 25, 1999

EUV jets and reconnection in the magnetic network

Evolution of a jet in Si IV 1393 Å visible as blue and red shifts in SUMER spectra

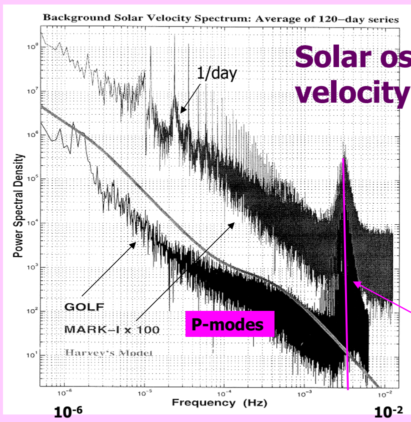
- **E-W step size 1", Δt = 5 s**

Jet head moves 1" in 60 s



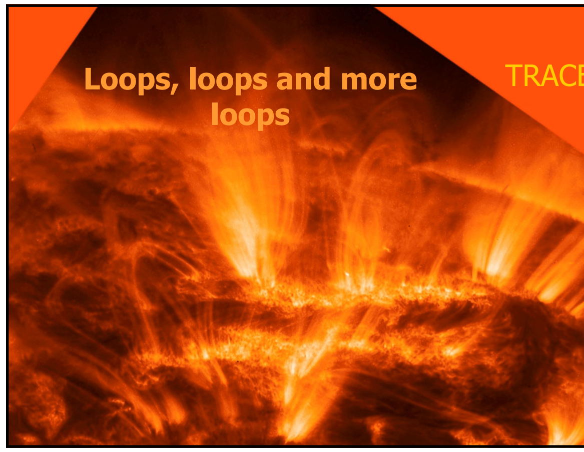
Innes at el., Nature, **386**, 811, 1997

Solar oscillations velocity spectrum



Cortes, 1998

Loops, loops and more loops



Characteristic time scales for the evolution of loops

- Dynamic time scale for restoration of pressure equilibrium:

$t_{dyn} = L/c_s = 1.1\ L_9/T_6^{1/2}$ [minutes]

- Conductive time scale for exchange of thermal energy:

$t_{con} = 3nk_BT\ l^2/(2\kappa_c T^{7/2}) = 30\ n_{10} l_9^2/T_6^{5/2} \approx 7(l_9/L_9)^2\ t_{dyn}$

- Radiative time scale for cooling by radiation losses:

$t_{rad} = 3n_e k_B T/(n_e n_H \Lambda(T)) \approx 5\ T_6^{5/3}/n_{10} = 35\ T_6^{1/6}\ t_{dyn}$

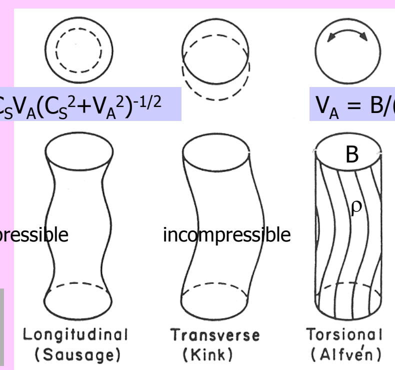
Legend: L, loop length; l, gradient scale length; c_s, sound speed; T, loop temperature; $\Lambda(T)$, radiative loss function; $L_9 = 10^9$ cm = 10 000 km; $T_6 = 10^6$ K; $n_{10} = 10^{10}$ cm^{-3}; κ_c = thermal conductivity.

Schrijver et al., Solar Phys. **187**, 261, 1999

Oscillations of magnetic flux tube

$C_T = C_S V_A (C_S^2 + V_A^2)^{-1/2}$

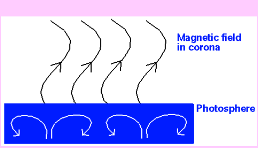
$V_A = B/(4\pi\rho)^{1/2}$



Magnetic and thermal pressure

Magnetic curvature force (tension)

MHD wave heating



Coronal magnetic field rooted down in turbulent photosphere

=> Waves!

- Generation of MHD waves driven by magneto-convection
- Phase mixing due to gradients
- Absorption at small scales

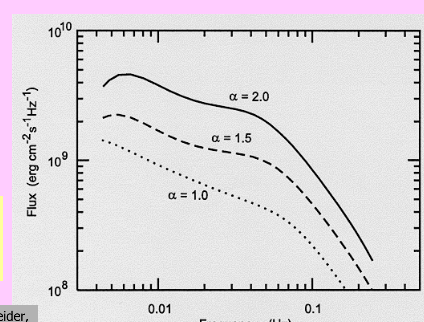
Process	Period/s
Alfvèn/fast magnetosonic	< 5
Sound/slow magnetosonic	< 200
Gravity	40
Conduction	600
Radiation	3000
Convection	> 300

Wave spectrum generation by turbulent shaking of flux tubes

Here α is the mixing length, $\lambda = \alpha$ H, with barometric scale height H.

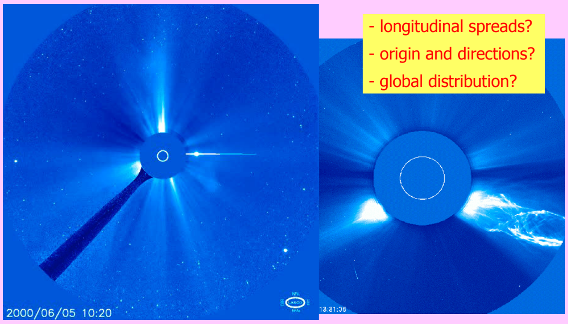
Photosphere: H=300 km.

Thin flux tube oscillations -> torsional Alfvén waves



Musielak & Ulmschneider, A&A, **386**, 606, 2002

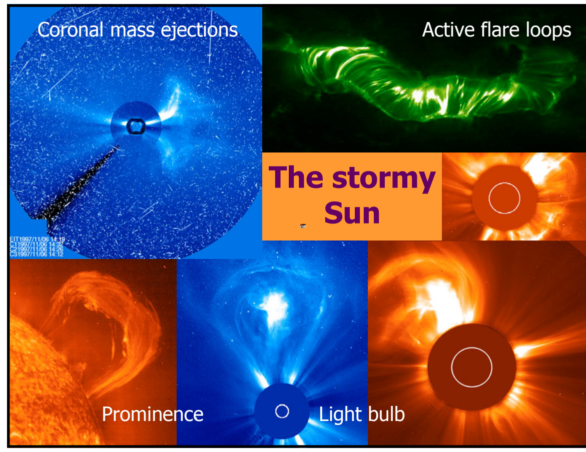
Coronal mass ejections



- longitudinal spreads?
- origin and directions?
- global distribution?

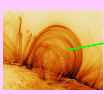
Schwenn et al., 1998, 2000

LASCO on SOHO, helical CME

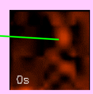


Coronal heating: a buzzword

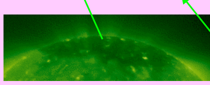
Coronal heating?



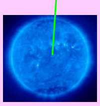
closed magnetic loops are observed at a wide range of temperatures



Small brightenings at a range of wavelenths



polar plumes are observed at "coronal" temperatures in open magnetic structure, the coronal holes



"diffuse" corona radiating at 2 MK is not confined to "bright" loops

special energy requirements in cool (10^4 K) prominence

Time and space dependence!

Coronal heating - an unsolved problem

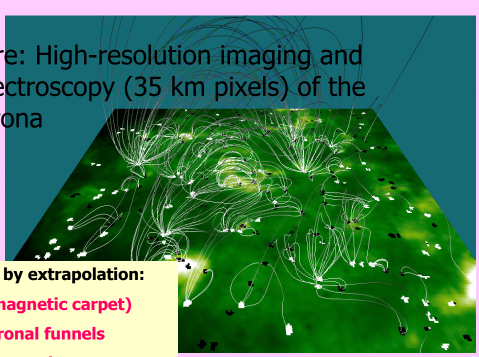
Why?

Facing complexity and variability:

- **Solar corona is non-uniform and highly structured**
- **Corona varies in time (magnetic activity cycle)**
- **Temporal and spatial changes occur on all scales**
- **Corona is far from thermal (collisional) equilibrium**
- **Coronal processes are dynamic and often nonlinear**

The elusive coronal magnetic field

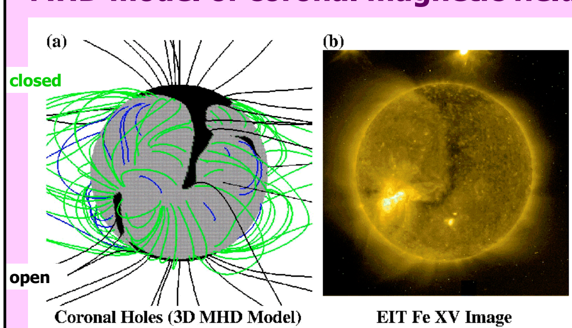
Future: High-resolution imaging and spectroscopy (35 km pixels) of the corona



Modelling by extrapolation:

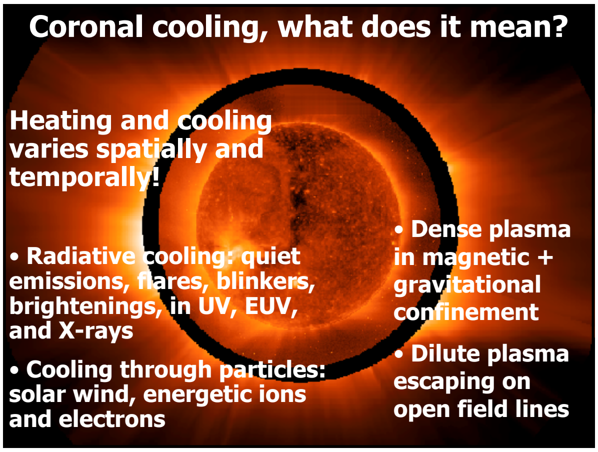
- Loops (magnetic carpet)
- Open coronal funnels
- Closed network

MHD model of coronal magnetic field



Linker et al., JGR, **104**, 9809, 1999

„Elephants trunk" coronal hole



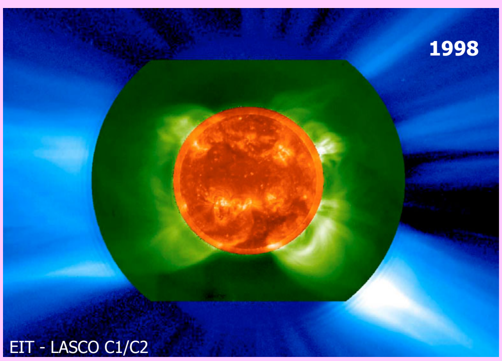
Fast solar wind parameters

- Energy flux at 1 R_S: $F_E = 5\ 10^5$ erg $cm^{-2}\ s^{-1}$
- Speed beyond 10 R_S: $V_p = (700 - 800)$ km s^{-1}
- Proton flux at 1 AU: $n_p V_p = 2\ 10^8\ cm^{-2}\ s^{-1}$
- Density at 1 AU: $n_p = 3\ cm^{-3}$; $n_\alpha / n_p = 0.04$
- Temperatures at 1 AU:

  $T_p = 3\ 10^5$ K; $T_\alpha = 10^6$ K; $T_e = 1.5\ 10^5$ K
- Heavy ions: $T_i \cong m_i / m_p T_p$; $V_i - V_p = V_A$

Schwenn and Marsch, 1990, 1991

Corona of the active sun



Thermodynamics of the corona

Entropy balance (advective change equals other entropy productions):

$$\partial s/\partial t + V \bullet \nabla s =$$

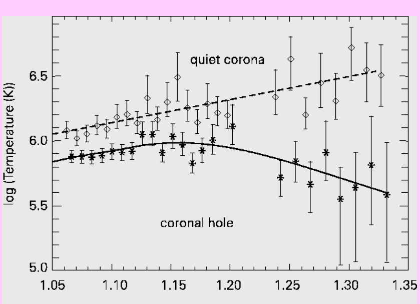
$$ds/dt|_R + ds/dt|_J + ds/dt|_V + ds/dt|_C + ds/dt|_M$$

Energy fluxes (in steady state the total flux is free of divergence):

$$\nabla \bullet (F_K + F_G + F_R + F_J + F_V + F_C + F_M) = 0$$

Kinetic + gravitational + radiative + ohmic + viscous + conductive + mechanical

Electron temperature in the corona



Streamer belt, closed

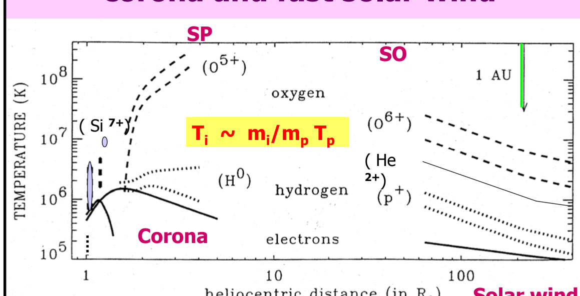
Coronal hole, open magnetically

David et al., A&A, **336**, L90, 1998

Heliocentric distance

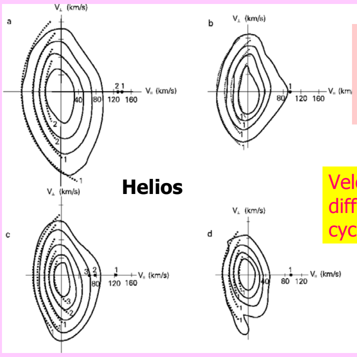
SUMER/CDS SOHO

Temperature profiles in the corona and fast solar wind



Cranmer et al., Ap.J., 2000; Marsch, 1991

Pitch-angle diffusion of solar wind protons



VDF contours are segments of circles centered in the wave frame (< V_A)

Velocity-space resonant diffusion caused by the cyclotron-wave field!

Marsch and Tu, JGR, **106**, 8357, 2001

Energy balance in the corona

Coronal loops:

Energy balance mainly between radiative cooling and mechanical heating

$$V \cdot \nabla s = ds/dt|_R + ds/dt|_M + ds/dt|_C$$

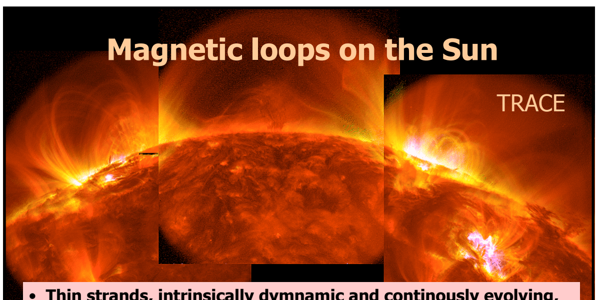
Coronal holes:

Energy balance mainly between solar-wind losses and mechanical heating

$$\nabla \cdot (F_K + F_G + F_M) = 0$$

$F_M = \rho V_{sw} (V^2_{sw} + V^2_{\infty})/2$ $\quad V_{\infty} = 618$ km/s

Magnetic loops on the Sun



- **Thin strands, intrinsically dymnamic and continously evolving,**
- **Intermittent heating (in minutes), primarily within 10-20 Mm,**
- **Meandering of hot strings through coronal volume,**
- **Pulsed injection of cool material from chromosphere below,**
- **Variable brightenings, by braiding-induced current dissipation?**

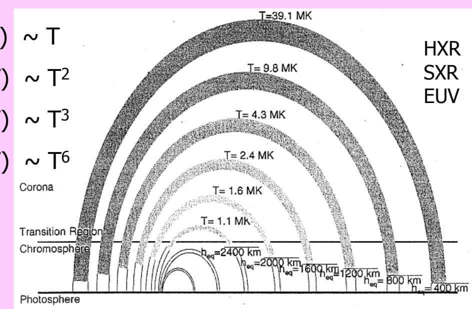
Empirical scaling laws for loops

$L(T) \sim T$

$n(T) \sim T^2$

$p(T) \sim T^3$

$E(T) \sim T^6$



Scale height for loop footpoints: $h_{eq}(T) \sim T^{-1/2}$
Lower cutoff: L_{min} = 5 Mm, E_{min} = 20^{24} erg

Aschwanden, Solar Phys. **190**, 233, 1999

Coronal heating mechanisms I

Wave (AC) mechanisms (generation, propagation, non-uniformity)

- Sound waves, shocks (barometric stratification), turbulence
- Magnetoacoustic (body, surface), Alfvén (resonance absorption)
- Plasma (dispersive) waves (Landau damping), ion-cyclotron waves

Current sheet (DC) mechanism (formation of sheets, flux emergence)

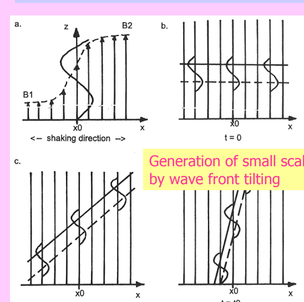
- Quasistatic current sheet formation in force-free fields
- Dynamic formation driven by flux emergence
- Field-aligned currents (ohmic and anomalous resistivity)

Heating by micro/nano/pico flares (magnetic field reconnection)

- Thermalization of energetic particles (Bremsstrahlung: radio to X-rays)
- Reconnection driven by colliding magnetic flux

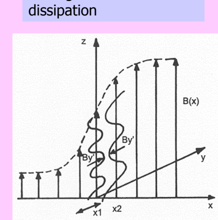
Coronal heating mechanisms II

Resonant absoption of magnetoacoustic surface waves on a field gradient



Generation of small scales by wave front tilting

Phase mixing leads to current sheets and small scale gradients -> dissipation



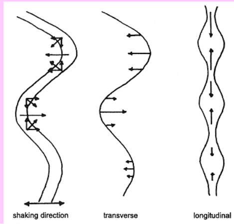
Ulmschneider, 1998

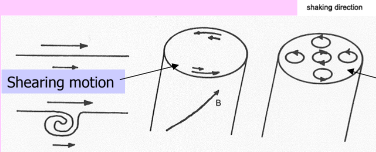
Coronal heating mechanisms III

Pressure equilibrium:
$p_e = p_i + B_i^2/8\pi$

Gas pressure: $p_e \approx 1$ dyn/cm^2
Equipartition field: $B_i \approx 1$ kG

- Generation by turbulence
- Wave mode couplings





Turbulent heating
Decay into smaller vortices or flux tubes

Heyvaerts & Priest, 1983

Coronal heating mechanisms IV

Heating by kinetic plasma waves
Absorption of high-frequency waves
Wave generation and transport?

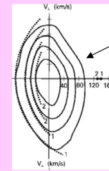
Damping rate: $\gamma/\omega \sim \partial f/\partial v$

- **Landau damping:** $\omega - \mathbf{k} \cdot \mathbf{v} = 0$
- **Cyclotron damping:** $\omega - \mathbf{k} \cdot \mathbf{v} \pm \Omega = 0$

Advantage: Processes occur at small scales, near the ion inertial length or gyroperiod,

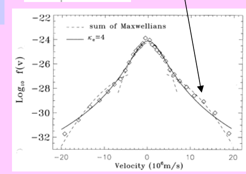
$l = V_A/\Omega, \ \tau = 2\pi/\Omega$

Problem: Velocity distribution are unknown; in-situ evidence for non-thermal features ->

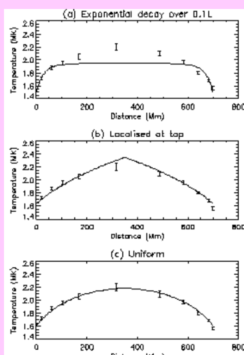


Anisotropic protons in solar wind

electrons with suprathermal tails



Measuring thermal structure of loops

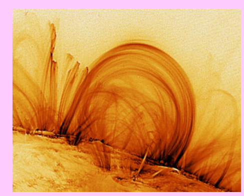


- **Yohkoh/SXT observations**
- **Spatially uniform heating**

Priest et al., 2000

Conclusions on thermal structure

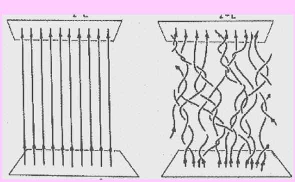
- Thermal loop structure is a possible heating diagnostic.
- But one must be careful on the interpretation of hydrostatic and LTE models.



Possible observational "solutions"

- Follow T(s) evolving in time, not just snapshots
- Spectrometer and imager working together (more in the future)
- Keep spectrometer slit at one position -> temporal variations only
- Velocity and density tracking as indicators of dynamics needed

Ubiquitous magnetic reconnection



Parker's (1988) nanoflare concept

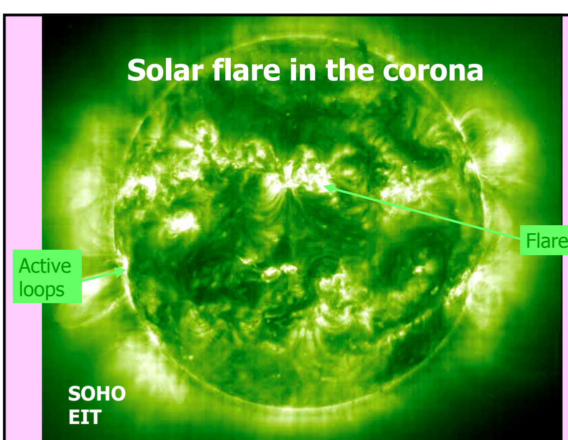
Power-law of flare frequency f **against energy** E

$$f(E) = f_0 E^{-\alpha}$$

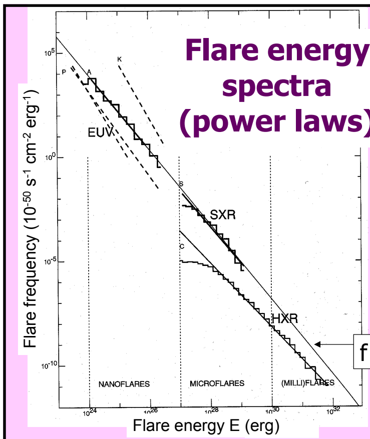
Spectral index, α **< -2, for nanoflare dominated heating**

Self-organised criticality :

- **Corona is modeled as an externally driven, dissipative dynamical system**
- **Larger catastrophes are triggered by a chain reaction of many smaller events**



Flare energy spectra (power laws)



Exponent α	Number
2.02-2.42	4497 (P)
2.53-2.50	11150 (K)
1.79 (0.08)	281 (A)
1.74	291 (S)
1.54	2878 (C)

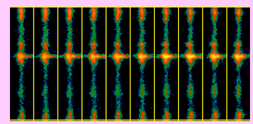
Sun's luminosity 3.38 10^{33} erg/s

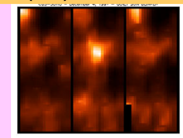
$f = E^{-\alpha}$

Aschwanden et al., 2000

Plethora of Brightenings

Active region transient brightenings (SXT), **Explosive events** (SUMER),
EUV brightenings (EIT, TRACE), **Blinkers** (CDS)....

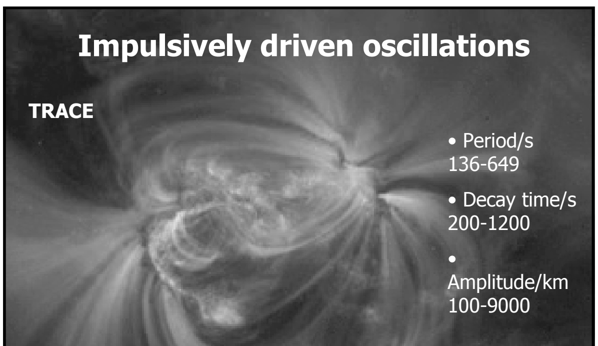




Explosive events (Innes et al., 1997)
- 2×10^5 K
- 60 s
- 160 kms^{-1}
- 2 arcsec (1500 km)

Blinkers (Harrison, 1997)
- 2×10^5 K
- 1000 s
- 20 kms^{-1}
- 10 arcsec (7500 km)

Impulsively driven oscillations



TRACE

- Period/s 136-649
- Decay time/s 200-1200
- Amplitude/km 100-9000

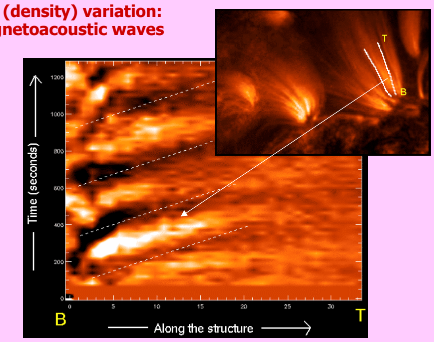
Schrijver et al. (2002) and Aschwanden et al. (2002) provide extensive overview and analysis of 17 cases of flare-excited transversal oscillations of coronal loops.

Detection of longitudinal waves

Intensity (density) variation: Slow magnetoacoustic waves

TRACE

Loop images in Fe 171 Å at 15 s cadence



De Moortel et al., 2000

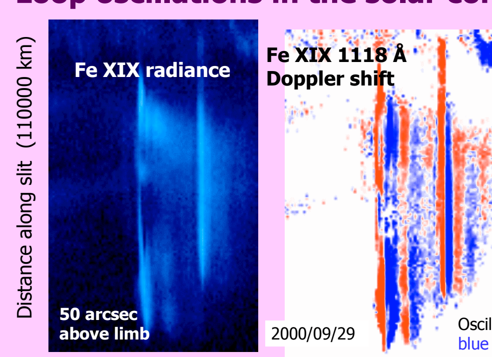
Loop oscillation properties

Parameter	Range
Footpoint length	10.2 - 49.4 Mm
Footpoint width	3.9 - 14.1 Mm
Transit period	1.3 - 6.3 s
Propagation speed	65 - 205 km s^{-1}
Relative amplitude	0.7 - 14.6 %
Damping length	2.9 - 18.9 Mm
Energy flux	195 - 705 mW m^{-2}

De Moortel, Ireland and Walsh, 2002

Statistical overview of the ranges of the physical properties of 38 longitudinal oscillations detected at the base of large coronal loops (1 R_S = 700 Mm).

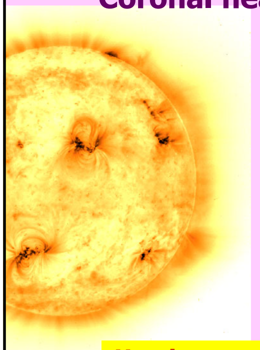
Loop oscillations in the solar corona



Wang et al., 2002

Time (240 minutes) Time ->

Coronal heating: Summary



- Corona, a restless, complex non-uniform plasma environment dominated by magnetic field
  - Evidence for quasi-periodic oscillations through the solar atmosphere and in loops
- Small-scale brightenings in a range of wavelengths and with power-law distribution in energy

Heating mechanisms remain unknown!