Sunshine: What message does it carry?

Solar radiation and spectrum
Radiation: definitions

- **Intensity** $I = \text{energy radiated per wavelength interval, surface area, unit angle and time interval.}

- **Flux** $F = I$ in direction of observer integrated over the whole Sun:

  $$F = 2\pi \int I \mu d\mu, \quad \text{where} \quad \mu = \cos \theta$$

- **$F r^2_\odot$** = radiation emitted by star in direction of observer

- **Irradiance** $S_\lambda = \text{solar flux at 1AU} = \frac{F r^2_\odot}{R^2_{\text{orbit}}}$
  - Spectral irradiance $S_\lambda = \text{irradiance per unit wavelength}$
  - Total irradiance $S_{\text{tot}} = \text{irradiance integrated over all } \lambda$
Hydrostatic equilibrium

- Sun is (nearly) hydrostatically stratified (this is the case even in the turbulent convection zone). I.e. gas satisfies:

\[ \frac{dP}{dz} = -g \rho = -\frac{gP}{\mu RT} \]

\((P\) pressure, \(g\) gravitational acceleration, \(\rho\) density, \(\mu\) mean molecular weight, \(R\) gas constant\)

- Solution for constant temperature:

\[ P = P_0 \exp(-z/H) \]

- Here \(H\) is the pressure scale height. \(H \sim T^{1/2}\) and varies between 100 km in photosphere (solar surface) and \(\sim 10^4\) km at base of convection zone and in corona.
Optical depth

- Let axis $z$ point in the direction of light propagation

- Optical depth: $\Delta \tau_v = -\kappa_v \Delta z$

where $\kappa_v$ is the absorption coefficient $[\text{cm}^{-1}]$ and $\nu$ is the frequency of the radiation. Light only knows about the $\tau_v$ scale and is unaware of $z$

$\rightarrow$ Integration over $z$: $\tau_v = -\int k_v(z)dz$

Every $\nu$ has its own $\tau_v$ scale (note that the scales are floating, no constant of integration is fixed)
The Sun in white light: Limb darkening

- In the visible, Sun’s limb is darker than solar disc centre ($\Rightarrow$ limb darkening)
- Since intensity $\sim$ Planck function, $B_v(T)$, $T$ is lower near limb.
- Due to grazing incidence we see higher near limb: $T$ decreases outward.
Rays emerging from disk-centre and limb

Rays near solar limb originate higher in atmosphere since they travel $1/\cos\theta$ longer path in atmosphere $\Rightarrow$ same number of absorbing atoms along path is reached at a greater height.
Limb darkening vs. wavelength $\lambda$

- short $\lambda$: large limb darkening;
- long $\lambda$: small limb darkening
- departure from straight line: limb darkening is more complex than $I(\theta) \sim \cos(\theta)$
The Sun in the FUV: Limb brightening

- At $\lambda < 150$ nm, Sun’s limb is brighter than disc centre (limb brightening)

- Most FUV spectral lines are optically thin

- Optically thin radiation comes from the same height everywhere

- Intensity $\sim$ thickness of layer contributing to it. Near limb this layer is thicker $\Rightarrow I \sim 1/\cos \theta$
Limb brightening in optically thin lines does NOT imply that temperature increases outwards (although by chance it does in these layers....)

Si I 125.6 nm
Solar irradiance spectrum

Irradiance = solar flux at 1AU

Spectrum is similar to, but not equal to Planck function

⇒ Radiation comes from layers with diff. temperatures.

Often used temperature measure for stars:

Effective temp: \( \sigma T_{\text{eff}}^4 = \text{Area under flux curve} \)
Spectrum above and under the Earth’s atmosphere

- Sunlight at Top of the Atmosphere
- 5777 K Blackbody Spectrum
- Radiation at Sea Level
Absorption in the Earth’s atmosphere

Fig. 1.2. Absorption in the Earth’s atmosphere. The edge of the shaded area marks the height where the radiation is reduced to 1/2 of its original strength. UV ultraviolet; V visible; IR infrared
Planck’s function

- Amplitude increases rapidly with temperature, area increases $\sim T^4$ (Stefan-Boltzmann law) $\Rightarrow$ from $\lambda$-integrated intensity we get (effective) temperature

- Wavelength of maximum changes linearly with temperature (Wien’s law)

- Planck function is more sensitive to $T$ at short $\lambda$ than at long $\lambda$
Limb darkening vs. wavelength $\lambda$

- **short $\lambda$:** large limb darkening;
- **long $\lambda$:** small limb darkening

Due to $T$-dependence of Planck function, both are consistent with a single $T(z)$ profile.
Optical depth and solar surface

- Radiation at frequency $\nu$ escaping from the Sun is emitted mainly at heights around $\tau_\nu \approx 1$.

- At wavelengths at which $\kappa_\nu$ is larger, the radiation comes from higher layers in the atmosphere.

- In solar atmosphere $\kappa_\nu$ is small in visible and near IR, but large in UV and Far-IR $\Rightarrow$ We see deepest in visible and Near-IR, but sample higher layers at shorter and longer wavelengths.
Height of $\tau = 1$, brightness temperature and opacity vs. $\lambda$
The solar spectrum: continua with absorption and emission lines

- Solar spectrum changes in character at different $\lambda$
- X-rays: Emission lines of highly ionized species
- EUV - FUV: Emission lines of neutral to multiply ionized species plus recombination continua
- NUV: stronger recombination (b-f) continua and absorption lines
- Visible: H$^-$ b-f continuum with absorption lines
- FIR: H$^-$ f-f continuum, increasingly cleaner (i.e. less lines as $\lambda$ increases, except molecular bands)
- Radio: thermal and, at longer $\lambda$, increasingly non-thermal continua
Solar UV spectrum

Note the transition from absorption lines (for $\lambda > 2000\text{Å}$) to emission lines (for $\lambda < 2000\text{Å}$)
FUV spectrum

The solar spectrum from 670 Å to 1620 Å measured by SUMER (logarithmic scale)

Lyman continuum

Ly α
Transitions forming lines and continua

Recombination, b-f transition: Continuum emission

Electron scattering, f-f transition: Continuum emission

Excitation, b-b transition: Absorption line

De-excitation, b-b transition: Emission line

Collisions
When are emission, when absorption lines formed?

- **Continua** are in general formed the deepest in the atmosphere (or at similar heights as the lines).
- **Absorption lines** are formed when the continuum is strong and the temperature (source function) drops outwards (most effective for high density gas)
  - Either photons or collisions excite the atom into a higher state. For a high gas density, atoms are de-excited by collisions & the absorbed photon is destroyed.
- **Emission lines** are formed when the temperature (source function) increases outwards and gas density is low:
  - If the gas density is low atom decays spontaneously to a lower state, emitting a photon.
Typical scenario (not to scale)

- Height $z$
- Temperature $T$, Source funct.
- Log(pressure) $\log(P)$

Visible / NIR
visible / FIR / UV
FUV / EUV
X-ray / Radio

f-f and b-f continuum of H$^-$
Absorption lines
Recombination continua

Emission lines; Recomb. continua
Lines w. emission cores
Emission lines
Recomb. continua
Weak and strong spectral lines: saturation

- 4 spectral lines with different strengths, i.e. different number of absorbing atoms along LOS. Parameterized by $\eta_0$
- As $\eta_0$ increases the line initially gets deeper, then wider, finally showing prominent wings

Figure kindly provided by J.M. Borrero
Diagnostic power of spectral lines

Different parameters describing line strength and line shape contain information on physical parameters of the solar/stellar atmosphere:

- **Doppler shift of line**: (net) flows in the LOS direction
- **Line width**: temperature and turbulent velocity
- **Area under the line (equivalent width)**: elemental abundance, temperature (via ionisation and excitation balance)
- **Line depth**: temperature (and temperature gradient)
- **Line asymmetry**: velocity gradients, $v$, $T$ inhomogenieties
- **Wings of strong lines**: gas pressure
- **Polarisation and splitting**: magnetic field
Effect of changing abundance

Higher abundance = more absorbing atoms, stronger absorption
Abundance given on logarithmic scale with abundance (H) = 12

Fe I = spectral line of neutral iron
Fe II = spectral line of singly ionized iron: Fe\(^+\)

Higher abundance = more absorbing atoms, stronger absorption
Abundance given on logarithmic scale with abundance (H) = 12
Effect of changing temperature on absorption lines

Low temperatures: Fe is mainly neutral $\Rightarrow$ strong Fe I, weak Fe II lines

High temperatures: Fe gets ionized $\Rightarrow$ Fe II strengthens relative to Fe I

Very high temperatures: Fe gets doubly ionized $\Rightarrow$ Fe II also gets weak
Effect of changing line-of-sight velocity on absorption lines

Shift in line profiles due to Doppler effect
Same magnitude of shift for all lines
Effect of changing microturbulence velocity on absorption lines

In a turbulent medium the sum of all Doppler shifts leads to a line broadening.
Solar convection

In addition to radiation, convection is the main form of energy transport. Convection dominates just below the solar surface and structures the lower solar atmosphere.
The convection zone

- Through the outermost 30% of solar interior, energy is transported by convection instead of by radiation.

- In this layer the gas is convectively unstable.

- I.e. the process changes from a random walk of the photons through the radiative zone (due to high density, the mean free path in the core is well below a millimeter) to convective energy transport.

- The unstable region ends just below the solar surface. I.e. the visible signs of convection are actually due to overshooting (see following slides).

- $t_{\text{radiative}} \sim 10^6 \text{ years} \gg t_{\text{convective}} \sim \text{days-weeks}$
Scales of solar convection

- **Observations:** 4 main scales
  - granulation
  - mesogranulation
  - supergranulation
  - giant cells

- **Colour:**
  - well observed
  - less strong evidence

- **Theory:** larger scales at greater depths. Most details are still unclear
Surface manifestation of convection: Granulation

- Typical size: 2 Mm
- Lifetime: 5-8 min
- Velocities: 1 km/s (but peak velocities > 10 km/s, i.e. supersonic)
- Brightness contrast: 15% in visible (green) continuum (under ideal conditions)
- All quantities show a continuous distribution of values
- At any one time $10^6$ granules on Sun
Surface manifestation of convection: Supergranulation

- 1 hour average of MDI Dopplergrams (averages out oscillations)
- Dark-bright: flows towards/away from observer
- No supergranules visible at disk centre: velocity is mainly horizontal
- Size: 20-30 Mm, lifetime: days, horiz. speed: 400 m/s, no contrast in visible
Spectral signature of granulation: Line bisectors

Doppler shifts

Individual profiles

Composite profiles

Brightness

With Velocity

No velocity

\( \Delta V \text{ [km/s]} \)
Observed line bisectors: "C" shape

FeI $\lambda$522.553
$x_{e^+} = 0.110$ eV
abundance = 7.18
NLTE Ionization

FeI $\lambda$550.679
$x_{e^+} = 0.990$ eV
abundance = 7.18
NLTE Ionization
Supergranules seen by SUMER

- **Si I 1256 Å full disk scan by SUMER in 1996**
- **Bright network:**
  found at edges of supergranulation cells
- **Darker cells:**
  supergranules
Supergranules & magnetic field

- Why are supergranules seen in chromospheric and transition region lines?
- Network magnetic fields are located at edges of supergranules.
- They appear bright in chromospheric and transition-region radiation (e.g. In UV)
Onset of convection

Schwarzschild’s instability criterion

Consider a rising bubble of gas:

\[ \rho^* < \rho_0 - \Delta \rho \]

Condition for convective instability: \( \rho^* < \rho_0 - \Delta \rho \)
Illustration of convectively stable and unstable situations

Convectively **stable**

Convectively **unstable**
Onset of convection II

For small $\Delta z$, bubble will not have time to exchange heat with surroundings: adiabatic behaviour. Convectively unstable if:

$$[(d\rho/dz)_{\text{rad}} - (d\rho/dz)_{\text{adiab}}] \Delta z < 0$$

$(d\rho/dz)_{\text{rad}}$ : stellar density gradient in radiative equilibrium

$(d\rho/dz)_{\text{adiab}}$ : adiabatic density gradient
Onset of convection II

Rewriting in terms of temperature and pressure:

\[ \nabla_{\text{ad}} = \left( \frac{d \log T}{d \log P} \right)_{\text{ad}} \]

\[ \nabla_{\text{rad}} = \left( \frac{d \log T}{d \log P} \right)_{\text{rad}} = \text{gradient in an atmosphere with radiative energy transport} \]

Schwarzschild’s convective instability criterion:

\[ \nabla_{\text{ad}} < \nabla_{\text{rad}} \]

Convectively stable

Convectively unstable
Why is radiative gradient so large in convection zone?
Ionisation of H and He

- Radiative gradient is large where opacity increases rapidly with depth. This happens where common elements get ionized (i.e. many electrons are released, increasing f-f opacity)

- Degree of ionisation depends on T and n_e:
  - H ionisation happens just below solar surface
  - He → He^+ + e^- happens 7000 km below surface
  - He^+ → He^{++} + e^- happens 30'000 km below surface

- Since H is most abundant, it provides most electrons (largest opacity) and drives convection most strongly

- At still greater depth, ionization of other elements also provides a minor contribution.
Convective overshoot

- Due to their inertia, the packets of gas reaching the boundary of the CZ pass into the convectively stable layers, where they are braked & finally stopped.

- **Overshooting convection**

- Typical width of overshoot layer: order of $H_p$

- This happens at both the bottom and top boundaries of the CZ and is important:
  - **Top boundary**: Granulation is overshooting material. $H_p \approx 100$ km in photosphere
  - **Bottom boundary**: the overshoot layer allows B-field to be stored → seat of the dynamo?
Convection simulations

- **3-D hydrodynamic simulations** reproduce a number of observations and provide new insights into solar convection.

- These codes solve for **mass conservation**, **momentum conservation** (force balance, Navier-Stokes equation), and **energy conservation** including as many terms as feasible.

- **Problem**: Simulations can only cover 2-3 orders of magnitude in length scale (due to limitations in computing power), while the physical processes on the Sun act over at least 6 orders of magnitude.

- Also, simulations can only cover a part of the size scale of solar convection, either granulation, supergranulation, or giant cells, but not all.
Simulations of solar granulation

Solution of Navier-Stokes equation etc. describing fluid dynamics in a box (6000 km x 6000 km x 1400 km) containing the solar surface. Realistic looking granulation is formed.
Testing the simulations

Comparison between observed and computed bisectors for selected spectral lines (2 computed bisectors shown: one each with and without oscillations in the atmosphere)
Granule structure

Upflows are broad & slow, downflows are narrow and fast. Why?