2 The Solar Surface and Exterior

The lowest layer in the atmosphere , which extends down to one optical depth is called the *photosphere*, within which much of the emergent blackbody temperature is established. **C & O, Sec. 11.2**

• The fact that the blackbody corresponds to just a single temperature, as opposed to a convolution of temperatures, implies that the scalelength for temperature gradients far exceeds the diffusive mean free path.

∗ The photosphere is around 500km thick.

• At the base of the photosphere, we see a patchwork of bright and dark regions that constantly change on timescales of 5-10 minutes. This effect is known as **granulation**, corresponding to spatial extents of 500-1000km.

Plot: SOHO UV Observations

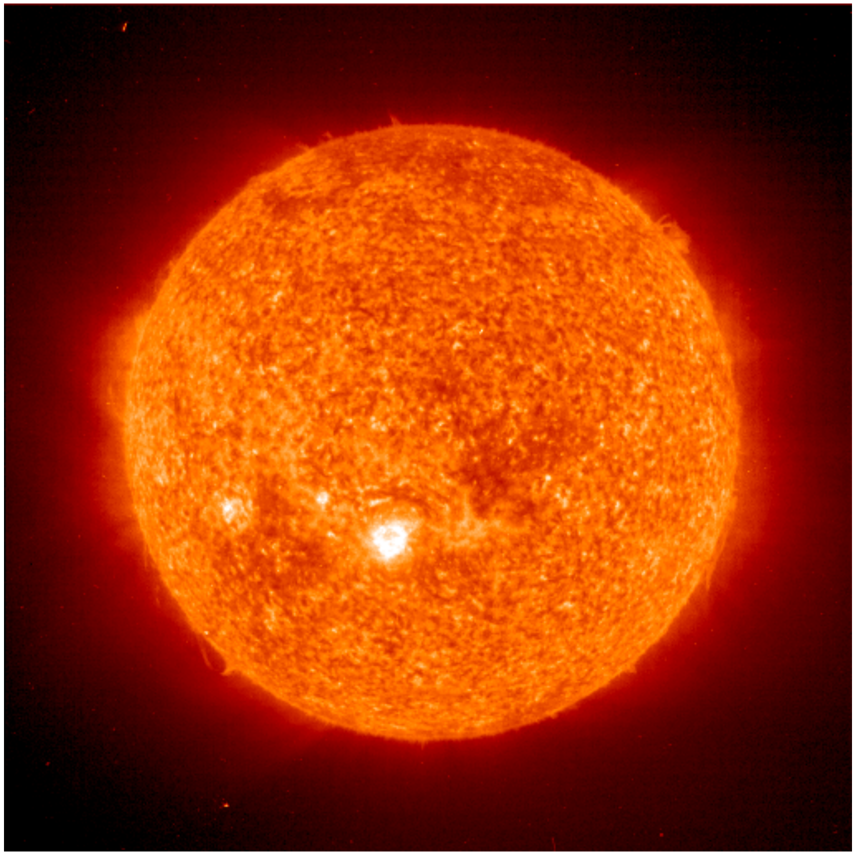
Granulation could occur on smaller scales, but we are limited by arcsecond resolution. Doppler shifting of spectral absorption lines in these granules on these variation timescales indicates rising (brighter) and falling (darker) bubbles at speeds of $0.4\,\mathrm{km/sec}$. *This signals convective energy exchange.*

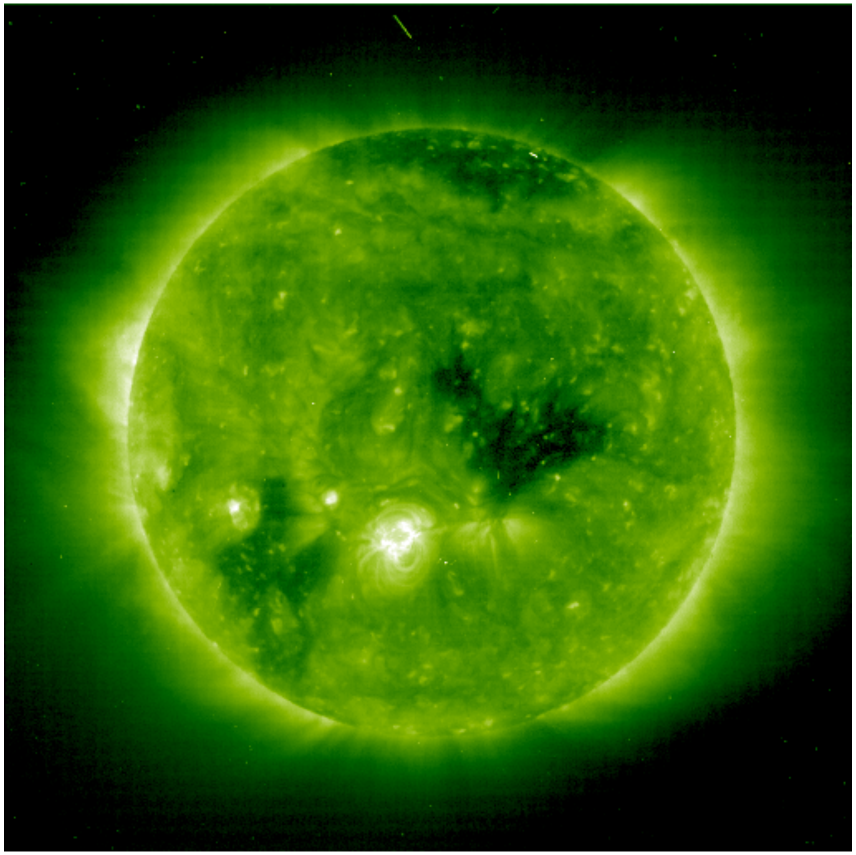
• The photosphere also contains a rather unique ion, H^-, where a second electron is loosely bound with an energy of $0.75\,\mathrm{eV}$. Such an ion can be neutralized by collisional stripping by photons blueward of 17,000 Å.

∗ This source of continuum opacity is primarily responsible for the smoothness of the solar spectrum in the visible and infra-red. Only about 1 in 10^7 hydrogen atoms exist as H^- in the photosphere.

• Above the photosphere are regions called the **chromosphere**, where the gas becomes somewhat hotter yet much more tenuous, at number densities of around 10^9 atoms per cubic centimeter. Then at heights above around 3000 km, there is the **corona**, where large and transient magnetic loops can drive plasma heating to X-ray and even soft gamma-ray temperatures.

Sun in UV: SOHO Observations





- Left panel: He lines showing convective granulation
- Right panel: Fe emission exhibiting coronal activity

• Coronal (flare) emission indicates the presence of both thermal and non-thermal particles. In this region, the sun connects to the heliosphere via the escape of **solar wind plasma** along open field lines (at **coronal holes**).

∗ The solar wind carries angular momentum due to the solar rotation; i.e. mass loss seeds spin-down, a feature common to main sequence stars.

∗ The flow of solar wind is described by **hydrodynamics** as opposed to hydrostatics, and specifically, since the magnetic field plays such a crucial role, the appropriate description is **magnetohydrodynamics**.

• This connection of the sun with interplanetary space defines a zone of influence called the **heliosphere**, extending out to the solar wind termination shock (boundary with interstellar space).

2.1 The Solar Cycle

Various transient features of the solar atmosphere provide an array of fascinating and complex phenomena. These include **sunspots**, dark patchy regions of the order of 10^4 km in diameter. They generally occur at *equatorial latitudes.* **C & O, Sec. 11.3**

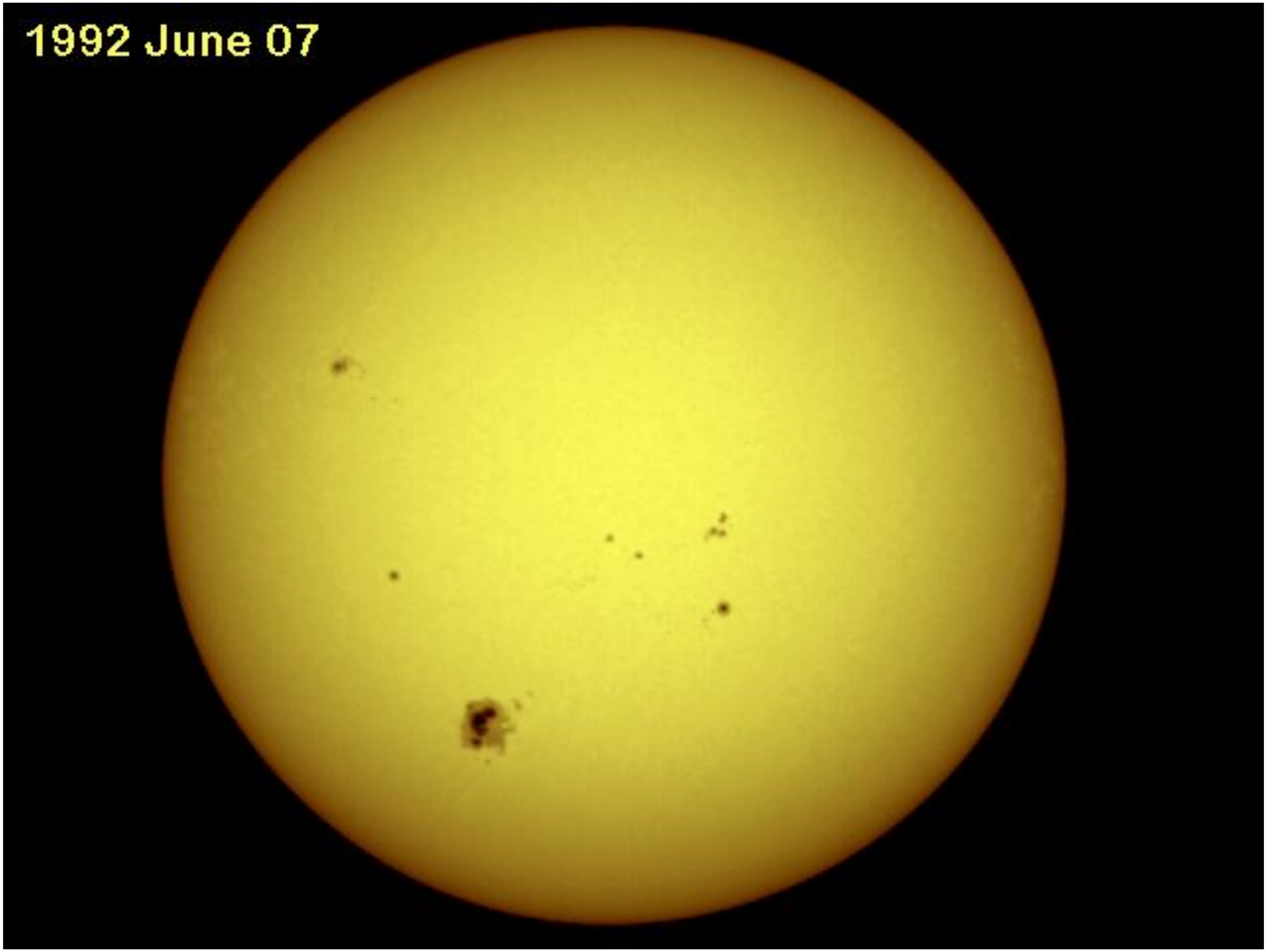
∗ The central umbra of a sunspot can be at temperatures as low as around $4000\,\mathrm{K}$, i.e. much lower than the mean surface temperature of $5770\,\mathrm{K}$.

∗ The typical lifetime of a sunspot is one to several months.

$\boxed{\textbf{Plot:}}$ Sunspots

• Sunspots are regions of intense magnetic field, which is measured via the Zeeman effect on spectral lines to be of the order of 1000 Gauss, three orders of magnitude higher than the typical solar surface field.

∗ The presence of intense magnetic fields can inhibit convective heating of the surface due to repulsion of bubbles by magnetic pressure, thereby explaining the cool nature of sunspots.


1992 June 07

• One of the oldest astronomical discoveries is that the number of sunspots evolves with an 11 year cycle, from **solar (sunspot) minimum** to **solar (sunspot) maximum** and back again.

∗ The latitudinal cycle reveals progressive epicyclic evolution toward the solar equator, forming the **butterfly diagram**.

Plot: Sunspot Cycle and Latitudinal Distribution

• The field polarity in sunspots (and elsewhere) is observed to reverse every 11 years so that global dipolar field and higher multipole fields complete a cycle every 22 years.

• Sunspots can cluster, and such clusters can be sites for dramatic eruptive events known as **solar flares**.

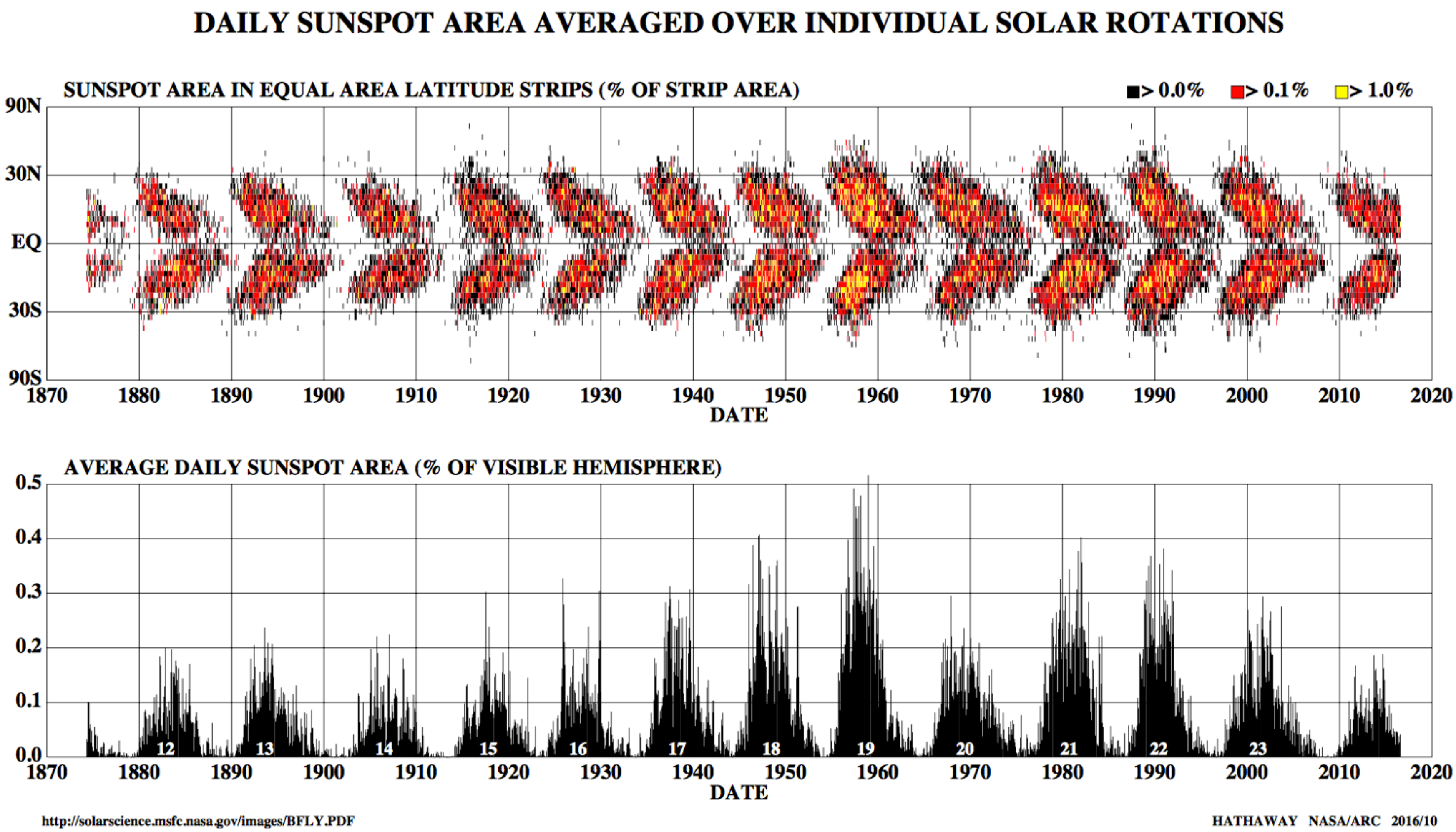
Plot: Solar Flare Light Curves and Schematic

The energy release is 10^{29} to 10^{32} ergs in a few minutes to an hour or so, on scales of as much as 10^5 km. Flares have intense *emission* lines due to the tenuous nature of their plasmas, and distinct nonthermal continuum emission such as radio synchrotron and X-ray bremsstrahlung, as well as nuclear excitation lines in the MeV band.

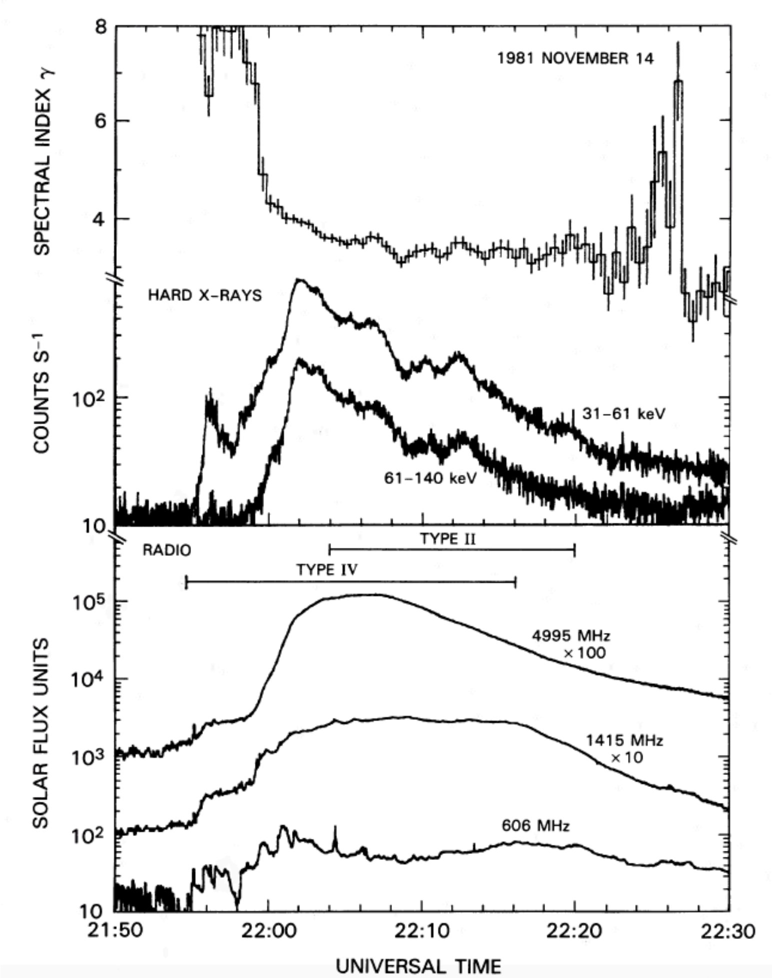
• Flares are loops of magnetic field and plasma bubbling off the surface, and can be connected to **coronal mass ejections** that trigger traveling interplanetary shocks in the heliosphere.

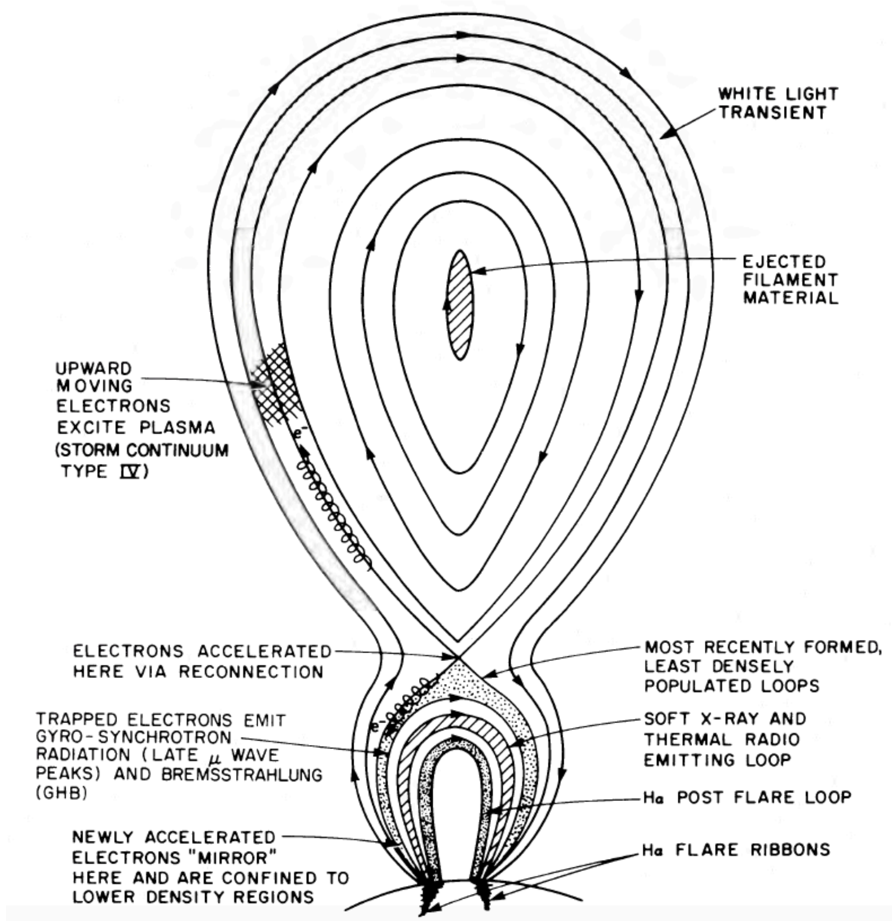
• Solar flares can disrupt terrestrial satellite and ground communications, and connect to the field of **space weather** in the terrestrial neighborhood.

Sunspot Butterfly Diagram



Solar Flare Light Curves and Schematic





- *Left panel*: Light curves of X rays (top) and decimetric radio waves (bottom)
- *Right panel*: A schematic model of a solar flare highlighting H_α flare ribbons and synchrotron electron acceleration. E. Cliver et al. (1986, ApJ **305**, 920)

9. STELLAR EVOLUTION I

Matthew Baring – Lecture Notes for ASTR 350, Fall 2021

1 Star Formation

The fact that the solar system is of an age considerably less than the Hubble time and that it has an unusually high metallicity suggests that it was formed from products of stellar evolution, i.e. preprocessing. **C & O, pp. 405–8**

Mass loss from stars can generate large clouds of gas and dust. Much of this can be neutral hydrogen, which can be mapped via the 21cm (1420 MHz) spin-flip transition in the radio. This hyperfine transition is used to map galactic rotation curves.

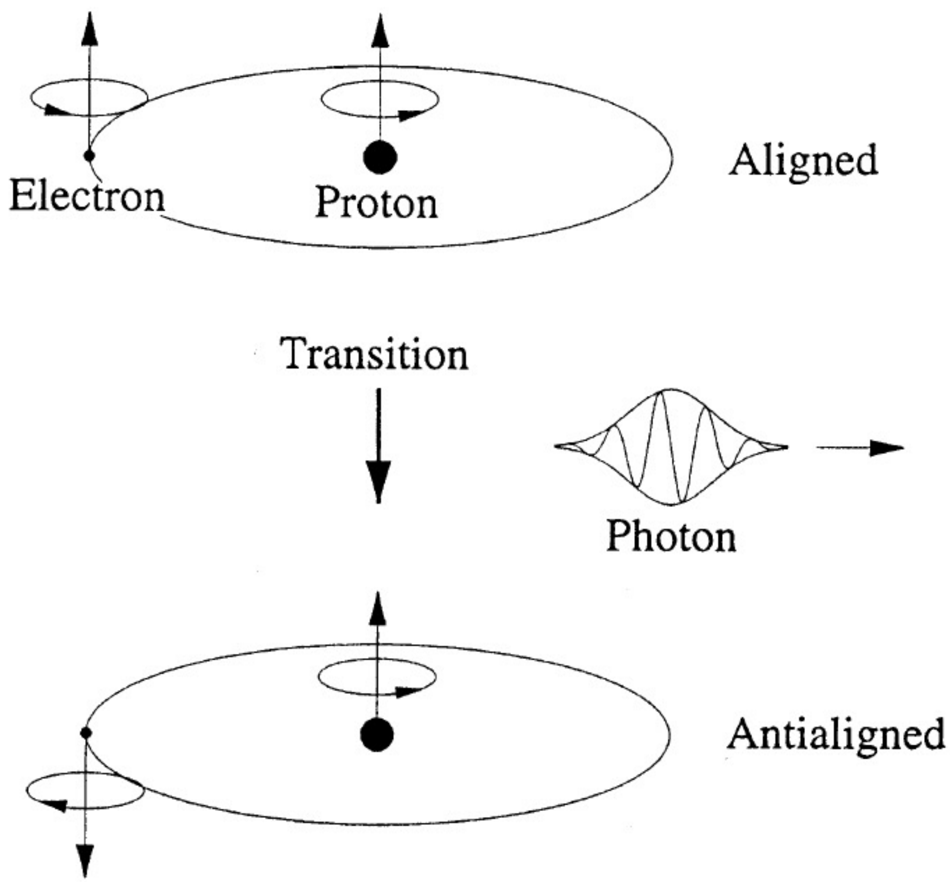
$\boxed{\textbf{Plot:}}$ 21cm Spin-Flip Transition

There are many **diffuse hydrogen clouds** in the galaxy, known also as **H I regions**, and they possess $T \sim 30 - 80\,\mathrm{K}$, number densities $n \sim 100 - 800$ cm^{-3} and masses $1 - 100 M_{\odot}$.

• Dust in such clouds can act as a site for hydrogen atoms to meet and coalesce into molecules. Moreover, the dust can shield the molecular hydrogen from radiative dissociation. Dusty clouds that have much of their hydrogen in molecular form are called **molecular clouds**.

∗ H_2 does not have any palpable radiative tracers in the radio or optical, unlike atomic hydrogen, so it is hard to discern directly. Instead, it is usually associated with other molecules, such as CO, so that these are used as tracers. Hence, molecular clouds are usually mapped in 2.6mm CO emission.

21 cm Spin-Flip Transition



- When the spins of the electron and proton in hydrogen transition from being aligned to anti-aligned, a 21cm (1420 MHz) wavelength photon is emitted.

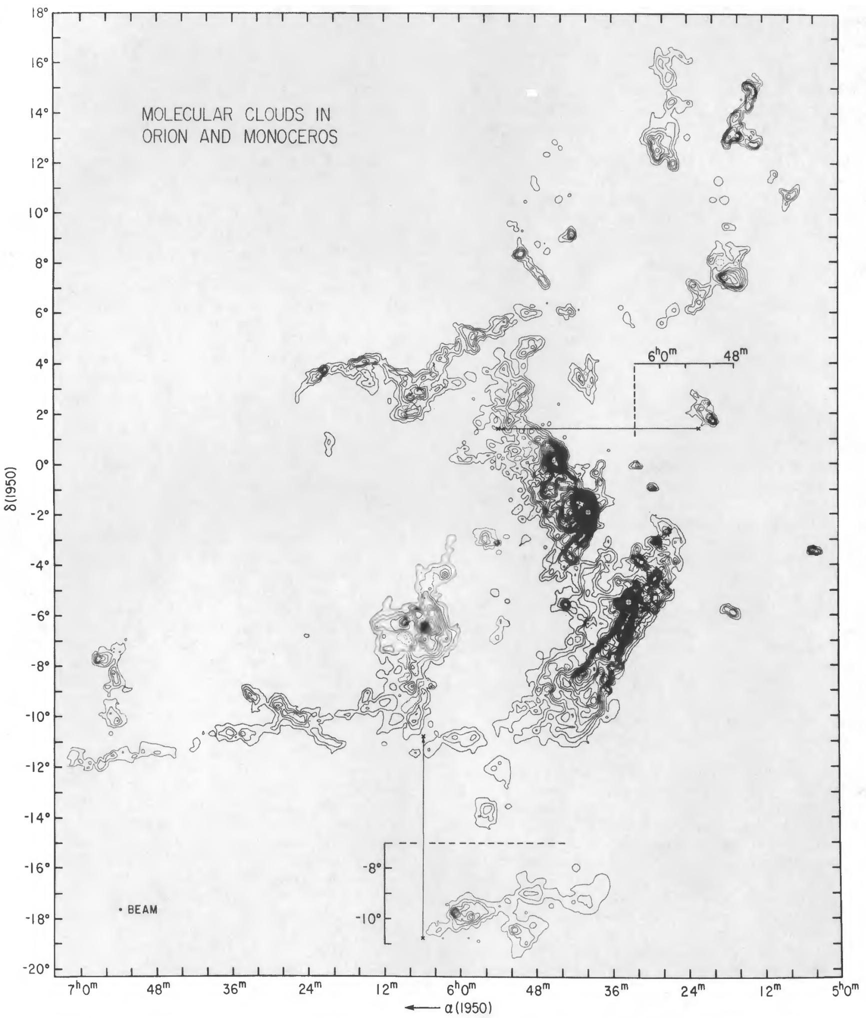
• **Giant molecular clouds** (GMCs) are enormous complexes of dust and gas, typically with radii $r \sim 50\,\mathrm{pc}$, with $T \sim 20-30\,\mathrm{K}$ and number densities $n \sim 100-300\ \mathrm{cm}^{-3}$. Residing within such clouds are **cores** (*draw schematic*) of radii $r \sim 0.1 - 1\,\mathrm{pc}$ and $T \sim 100 - 200\,\mathrm{K}$ and $n \sim 10^7 - 10^9\ \mathrm{cm}^{-3}$.

$\boxed{\textbf{Plot:}}$ Orion and Monoceros Molecular Clouds

$*$ The existence of **fragmentation** into such cores, with masses typically around $10 - 1000 M_\odot$, indicates that they are the sites of star formation.

$*$ Thousands of GMCs are known in our galaxy, mostly in the spiral arms.

Orion-Monoceros Molecular Cloud Complex



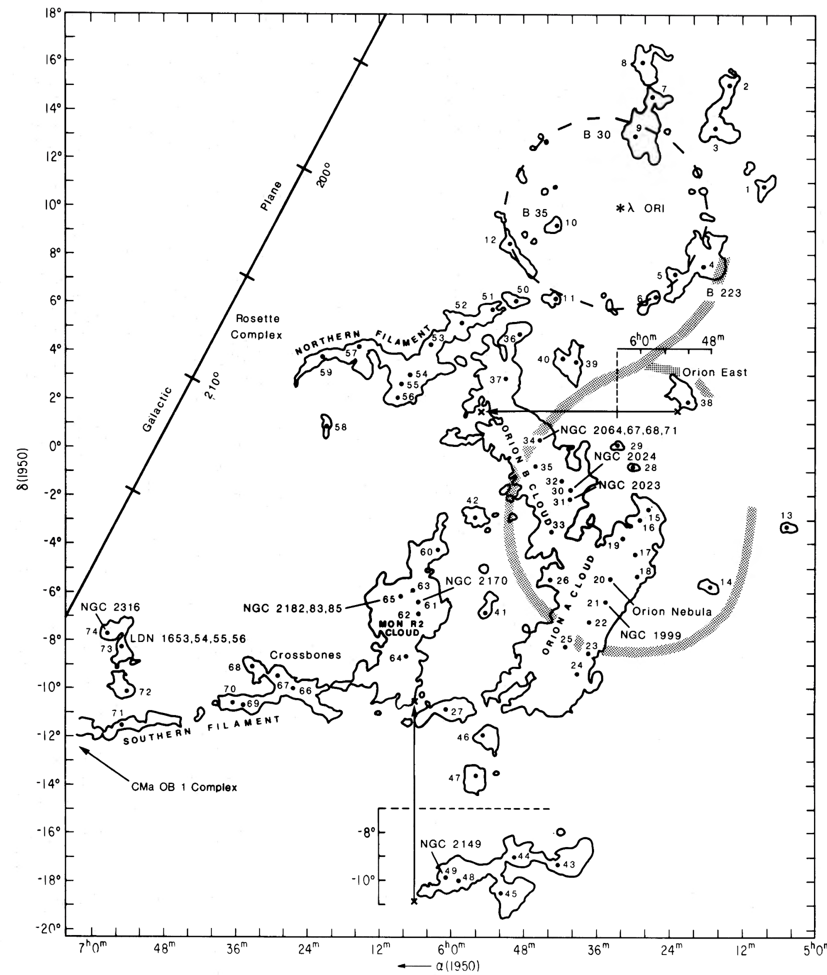


FIG. 3.—Schematic diagram of the molecular clouds: the lowest contour from Fig. 2. Dots with numbers, corresponding to those in Table 1, indicate locations of CO emission peaks. Some NGC numbers indicate the optically prominent objects coincident with CO peaks. The extent of UV emission from Barnard's loop is indicated by the shaded arc (from O'Dell, York, and Henize 1967; Isobe 1973). The dashed line roughly indicates the extent of the λ Ori ring of clouds.

- *Left panel*: CO map. *Right panel*: schematic highlighting cloud cores.
- From: R. Maddalena et al. (1986, ApJ **303**, 375)