Introduction to Astrophysics and Cosmology

Stellar Physics - Stellar evolution + the Sun

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Stellar models and observations

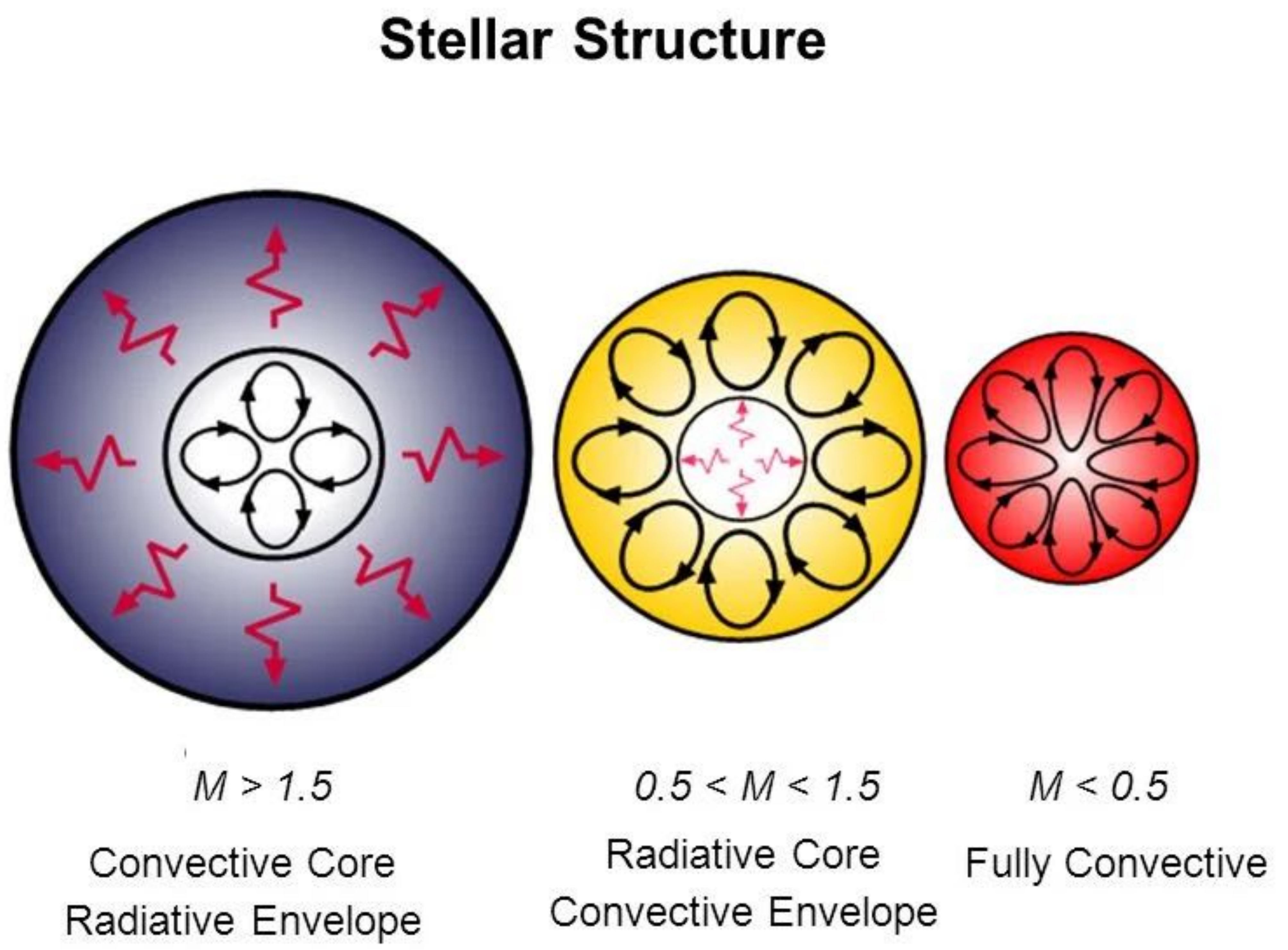
- We now understand in principle how a stellar model is constructed. The equation of state $P(\rho, T, Xi)$, the opacity $\chi(\rho, T, Xi)$ and the nuclear energy generation rate $\varepsilon(\rho,T,Xi)$ all depend on the chemical composition of the star.
- We need to specify the composition, keeping in mind that the **composition changes continously due to nuclear reactions** – at least in the core where these reactions take place.
- To construct the model of a star of a definite mass, usually an initial **uniform composition is assumed and first** a stellar model is calculated on the basis of it. This model would correspond to a star of this mass when it is just born.
- Then one finds out how the composition of the core will change due to nuclear reactions after some time. A stellar model calculated with this changed composition corresponds to the star some time after it is born.
- **By constructing successive models with changed compositions, one finds how the star evolves with time.** While hydrogen is being converted into helium in the core of a star, the overall structure of the star is found not to change much and the star lies on the main sequence in the HR diagram.
- Only **when hydrogen is depleted** sufficiently in the core, **drastic changes** in the overall characteristics of the star start taking place.

Stellar models and observations

- Many properties of stars can be understood without solving the stellar structure equations in detail.
  - **More massive stars are more luminous and hotter**, i.e. both their surfaces and central regions are hotter than surfaces and central regions respectively of less massive stars.
  - The **CNO cycle** must be the main **hydrogen burning process for more massive stars**, whereas the ***pp* chain** is the main hydrogen burning process for **less massive stars** (up to stars slightly heavier than the Sun).
- From the exponential factors it follows that ϵ_{CNO} is a much more rapidly increasing function of temperature than ϵ_{pp}. As a result, **the CNO cycle in the core of a massive star tries to create a steep temperature gradient.**
- A steep temperature gradient is likely to violate the Schwarzschild stability condition, **giving rise to convection**.
- **Massive stars have convective cores**, whereas the cores of less massive stars are stable against convection.

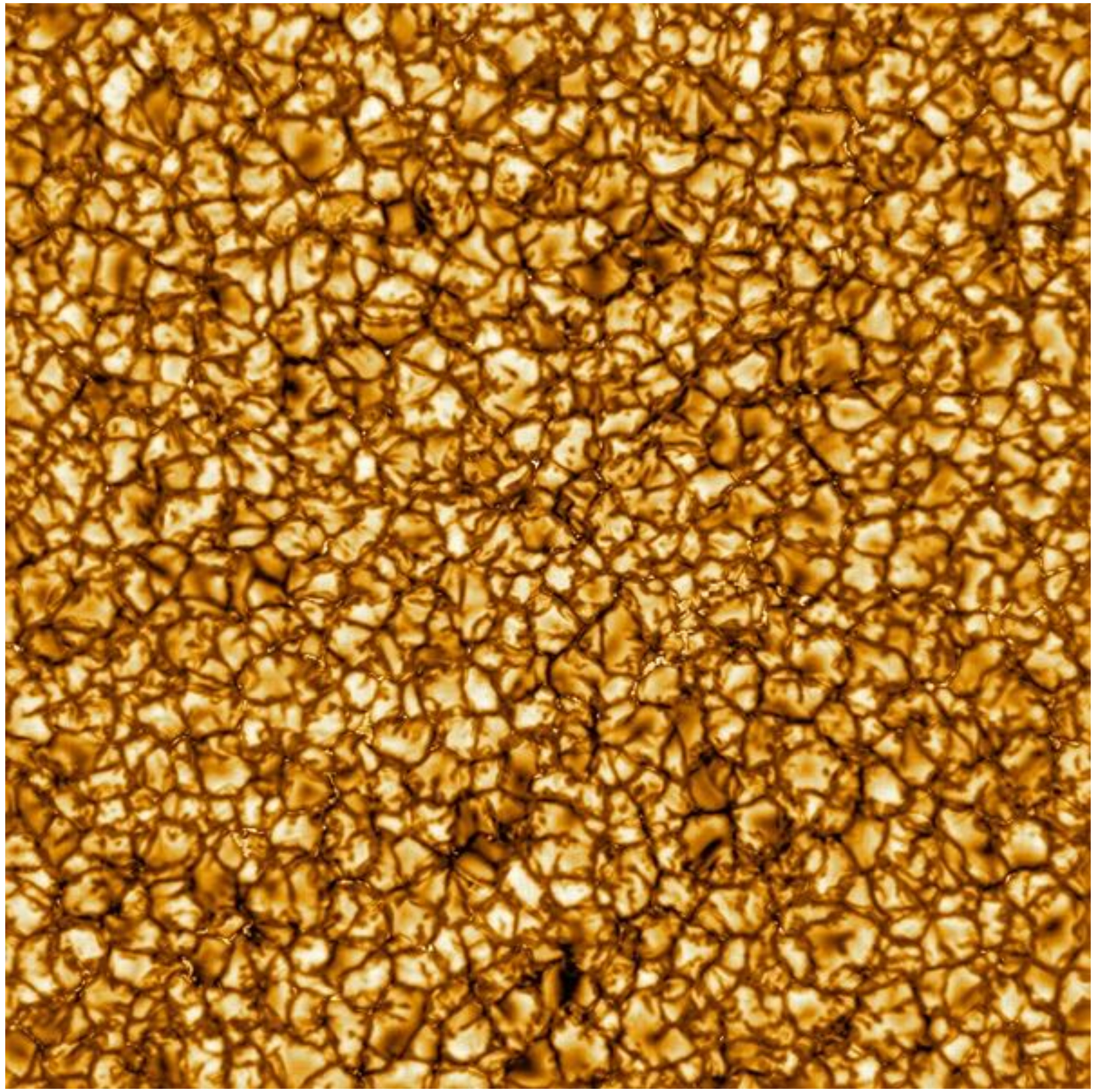
Stellar models and observations

- In the case of less massive stars, the temperature in the outer layers just below the surface is less than the temperature in the outer layers of more massive stars.
- A Kramers's law shows that the **opacity should be higher in the outer layers of less massive stars**. If the energy flux were to be carried by radiative transfer the temperature gradient will have to be steep if the opacity was high. We expect the Schwarzschild condition to be violated and the energy flux to be carried by **convection in the regions where opacity is high**.
- To sum up, more **massive stars have convective cores surrounded by stable envelopes, whereas less massive stars have convective envelopes surrounding stable cores.**
- The smallest stars can be fully convective.



Stellar models and observations

- It follows from the standard solar model that the **Sun has a stable core up to a radius of about $0.7R_{\odot}$, beyond which** the temperature gradient is unstable and **heat is transported by convection.**
- This theoretical conclusion is corroborated by high-quality images of the solar surface like the one in Figure
- This image gives the impression that we are looking at the top of a layer of convecting fluid. Since the upcoming hot gases are brighter and the down going cold gases are darker, we get the granular pattern which changes in a few minutes.



https://astronomy.com/news/2020/01/see-the-most-detailed-picture-of-the-suns-surface-ever-taken

The Sun seen by the
Inouye Solar Telescope

https://www.youtube.com/watch?v=znBesUwVOok&t=38s&ab_channel=SciNews

Stellar models and observations

- Convection observed on the star: R Doradus
- R Doradus is a Sun like star in terms of its mass, but it is already in the red giant phase, with a radius ~350 times larger than the Sun's radius
- The convective cells are ~75 times larger than the size of the Sun

https://www.eso.org/public/news/eso2412/

Stellar models and observations

- One of the main triumphs of stellar structure theory is that it can account for various properties of the stars on the main sequence (mass–luminosity relation and colour–magnitude relation).
- Stellar structure theory has led to very detailed stellar models constructed by many theorists over the years.
- **Is there some way to test if these detailed theoretical stellar models are indeed close to reality?**
- **Do densities, temperatures and pressures vary in the interiors of stars exactly in accordance with these theoretical stellar models?**

Helioseismology

What is helioseismology?

Helioseismology

- The **surface of the Sun is continuously oscillating** with periods of the order of a few minutes.
  - We know that an air column in a pipe vibrates only at some eigenfrequencies.
  - The analysis of the solar oscillations revealed the existence of many discrete frequencies.
  - The observed oscillations are essentially superpositions of many modes with discrete eigenfrequencies. By now several thousands of eigenfrequencies have been measured very accurately.
  - The **eigenfrequencies of an air column depend on the length of the column and the sound speed inside it,** since sound waves **travel back and forth** inside the column to set up the **standing modes**.
- Similarly, **the eigenmodes of the Sun are caused by sound waves** (we would call them 'sound waves' even though their frequencies are usually outside the audible range) which interfere constructively after passing through and around the Sun.
- Since different modes go up to different depths in the interior of the Sun, the **analysis of many modes together tells us how the sound speed varies with depth in the interior of the Sun.**

Helioseismology

- The sound speed is given by

$$c_s = \sqrt{\frac{\gamma P}{\rho}}$$

- Once **sound speeds at different depths** are inferred from helioseismology, one can **determine the density as a function of depth** inside the Sun.
- Figure 4.7 shows how the density, inferred from helioseismology and calculated from the standard model, differ from each other.
- The difference is considerably less than 2% at all depths. Thus **helioseismology has verified the standard solar model to a very high degree of accuracy.**

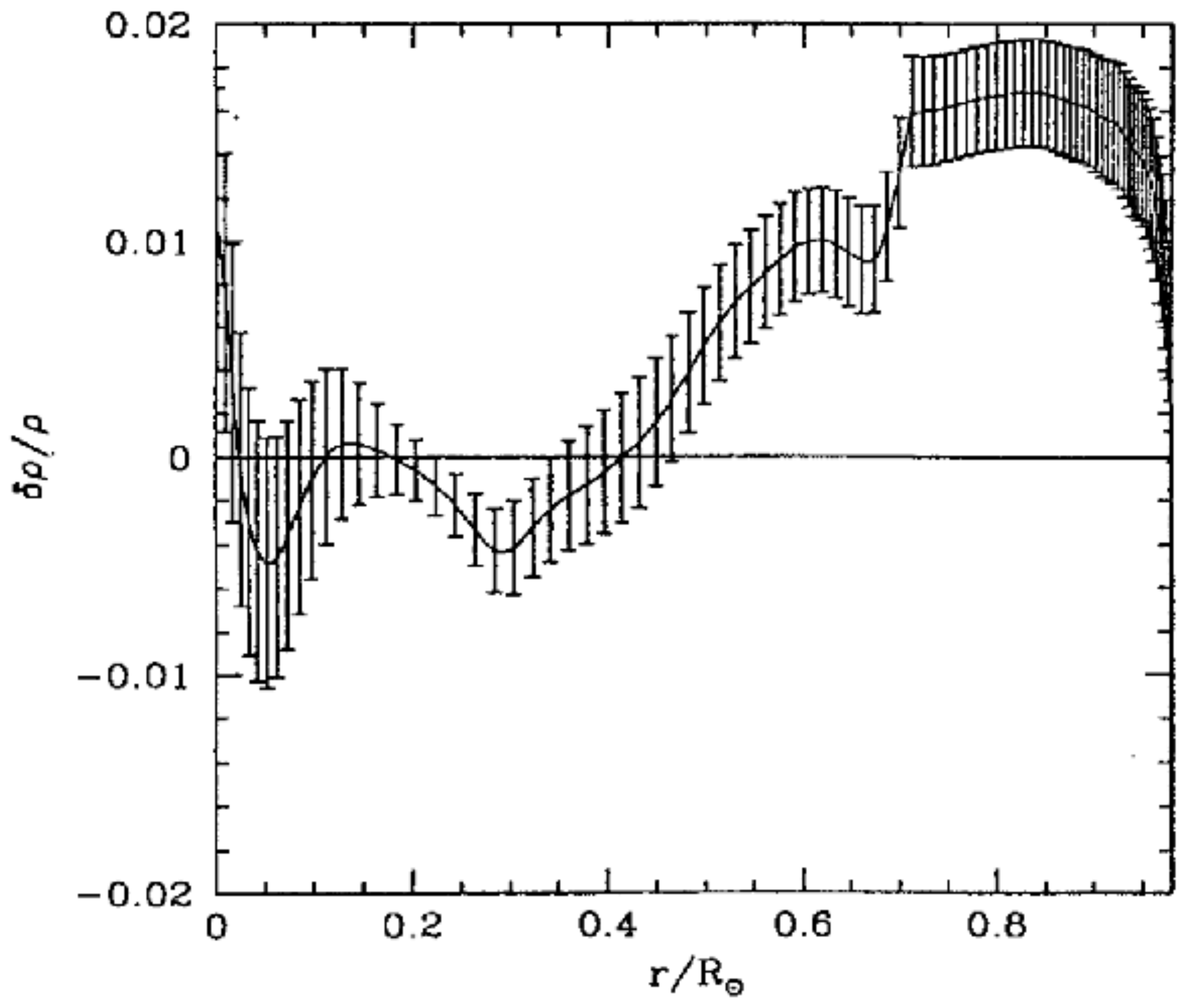
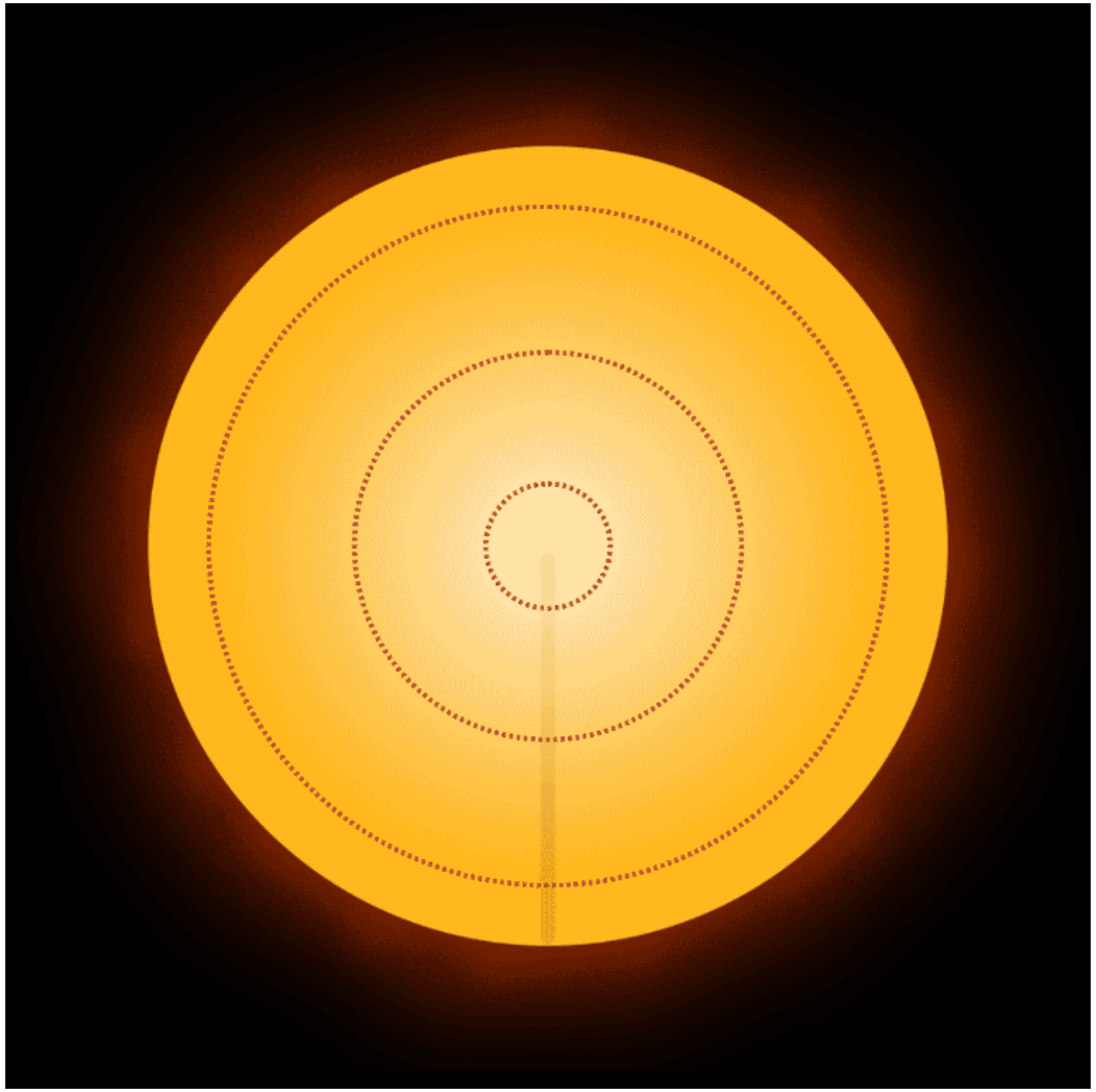


Fig. 4.7 The difference between the density inferred from helioseismology and the density calculated from the standard solar model (divided by the density), as a function of the solar radius. From Chitre and Antia (1999). (©Indian Academy of Sciences. Reproduced with permission from *Current Science*.)

Asteroseismology

- **Asteroseismology involves using the oscillation frequencies of a star to measure its internal properties.**
- A star is a gaseous sphere and will oscillate in many different modes when suitably excited. The frequencies of these oscillations depend on ***the sound speed inside the star, which in turn depends on density, temperature, gas motion and other properties of the stellar interior.***
- This analysis, called asteroseismology, yields information such as **composition, age, mixing and internal rotation** that cannot be obtained in any other way and is completely analogous to the seismological study of the interior of the Earth.



https://sifa.sydney.edu.au/asteroseismology/

Solar neutrino experiments

- Energy inside stars is produced by nuclear fusion.
- However, many aspects of observational data can be explained to a reasonable extent without any detailed knowledge of the energy generation process.
- **So, can we have an independent experimental check that nuclear reactions are really taking place inside stars?**

Solar neutrino experiments

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- However, many aspects of observational data can be explained to a reasonable extent without any detailed knowledge of the energy generation process.
- **So, can we have an independent experimental check that nuclear reactions are really taking place inside stars?**

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \longrightarrow {}^{2}\mathrm{H} + e^{+} + \nu,$$
$$^{2}\mathrm{H} + {}^{1}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \gamma.$$

$$\begin{aligned}
pp2: \; {}^{7}\mathrm{Be} + e^{-} &\longrightarrow {}^{7}\mathrm{Li} + \nu, \\
{}^{7}\mathrm{Li} + {}^{1}\mathrm{H} &\longrightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}. \\
pp3: \; {}^{7}\mathrm{Be} + {}^{1}\mathrm{H} &\longrightarrow {}^{8}\mathrm{B} + \gamma, \\
{}^{8}\mathrm{B} &\longrightarrow {}^{8}\mathrm{Be} + e^{+} + \nu, \\
{}^{8}\mathrm{Be} &\longrightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}.
\end{aligned}$$

Solar neutrino experiments

- Neutrinos are a by-product in many of the nuclear reactions.
- Since neutrinos interact with matter only through the weak interaction, most of the neutrinos created at the centre of the Sun would come out without interacting with the material of the Sun at all.
- Thus, at the Earth, **we expect a flux of neutrinos directly coming from the centre of the Sun**.
- Detecting this flux of neutrinos is a sure way of **confirming that nuclear reactions** are indeed taking place in the centre of the Sun.
- In the 1960s the famous first solar neutrino experiment began. The flux of neutrinos was detected, but the experimentally measured flux was found to be about one-third of what was theoretically predicted.

Solar neutrino experiments

$$pp2: \ {}^{7}\mathrm{Be} + e^{-} \longrightarrow {}^{7}\mathrm{Li} + \nu,$$

- Nuclear reactions which produce neutrinos:
- In the first reaction of, ${}^{7}Be$ gives rise to a neutrino besides a nucleus ${}^{7}Li$. Since there are **only two end products**, the conservations of momentum and energy easily show that **each of the product particles should have a specific value of energy**.
  - The ${}^{7}Be$ neutrino can have two discrete energies: 0.38MeV and 0.86 MeV.
- There are two other important reactions producing neutrinos:
  - the first reaction - *pp* neutrinos
  - the second reaction - ${}^{8}B$ neutrinos.
- In both these cases, the neutrino is **one of the three end products**. So it is possible for the neutrino to have **a distribution of energy**.
- The *pp* neutrinos have energy in the range 0–0.4 MeV, whereas the ${}^{8}B$ neutrinos have the energy range 0–15 MeV.

$$ {}^{1}\mathrm{H} + {}^{1}\mathrm{H} \longrightarrow {}^{2}\mathrm{H} + e^{+} + \nu,$$

$$ {}^{8}\mathrm{B} \longrightarrow {}^{8}\mathrm{Be} + e^{+} + \nu,$$

Solar neutrino experiments

- The vertical axis is logarithmic and the flux of ^8B neutrinos is several orders smaller than the flux of *pp* neutrinos.
- The **flux of ^8B neutrinos depends sensitively on the solar model**, since these neutrinos are produced in a reaction in the *pp*3 branch. This branch becomes more important if the temperature is higher.
- In a different solar model with a lower central temperature the ^8B neutrino flux can be considerably less.
- The *pp* neutrinos come from the main nuclear reaction. The luminosity of the Sun fixes the number of reactions taking place per unit time and determines the ***pp* neutrino flux**. The value of this flux, therefore, is **independent of the solar model** used.

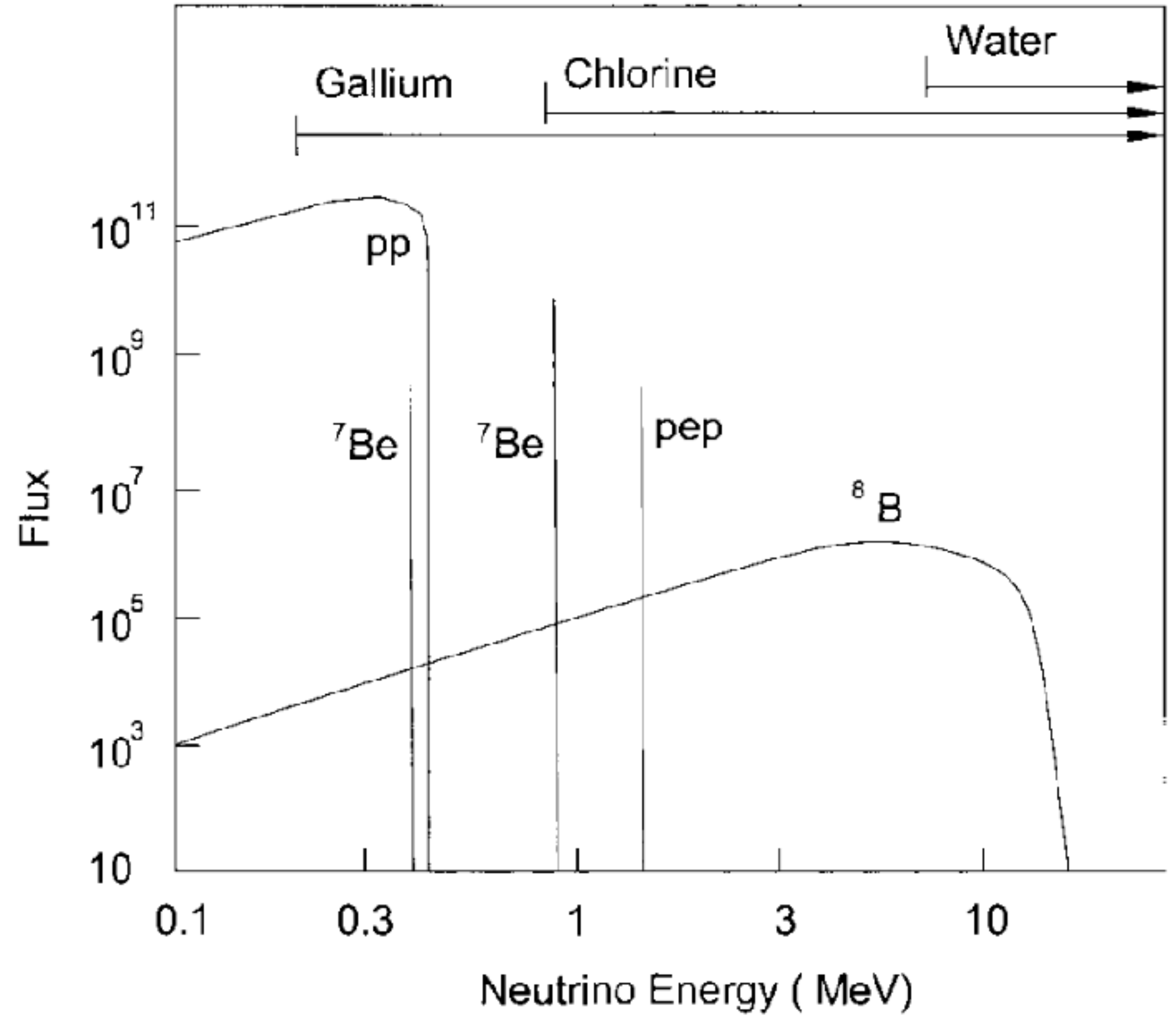


Fig. 4.8 The expected spectrum of the solar neutrino flux, based on the standard solar model. The detection ranges of the different experiments are indicated. Adapted from Bahcall (1999).

Solar neutrino experiments

Since neutrinos interact so weakly with matter, it is not easy to detect them. The pioneering **radio-chemical experiment** used the following reaction

Which decay process is this?

$$^{37}\text{Cl} + \nu \rightarrow {}^{37}\text{Ar} + e^-,$$

- for which the threshold neutrino energy is 0.814 MeV, as indicated in Figure -> **only the ^8B neutrinos** can produce this reaction.
- A huge tank of the cleaning fluid C_2Cl_4 was placed deep underground in a gold mine, to cut down the disturbances expected at the terrestrial surface. Neutrinos are the only particles which penetrated to this depth and occasionally interacted with a ^{37}Cl nucleus to produce ^{37}Ar.
- Since ^{37}Ar is radioactive, one could **estimate the solar neutrino flux based on radioactive decays**.
- A convenient unit to express the neutrino flux measurement is **SNU (Solar Neutrino Units)**, defined as 10^{-36} interactions per target atom per second.
- The chlorine experiment has fixed the flux to a value 2.56 ± 0.23 SNU on the basis of **25 years of operation,** whereas the theoretical value predicted by the standard solar model is 7.7 ± 1.2 SNU.

Solar neutrino experiments

- Two experiments in Japan – **Kamiokande and SuperKamiokande** – used pure water, in which neutrinos with energy above 7MeV can scatter electrons to high velocities which produce **Cherenkov radiation**.
- Using an array of **Cherenkov detectors**, it was possible to ascertain the **direction** from which the neutrinos were coming and to show for the first time that **neutrinos were really coming from the Sun**.
- Again only the ^8B neutrinos could be detected and the **flux was found to be half of what was theoretically predicted.**
- **What is the reason for this?**

Solar neutrino experiments

- We know that there are **three kinds of neutrinos:** *the electron neutrino* ν_e*, the muon neutrino* ν_μ *and the tau neutrino* ν_τ.
- If neutrinos **have non-zero mass**, then it can be shown that it is possible for one type of **neutrino to get spontaneously converted into other types**. This is called **neutrino oscillation.**
- The **nuclear reactions in the Sun produce electron neutrinos** and all the solar neutrino experiments also **detect electron neutrinos only**.
- During the flight from the Sun to the Earth, some of the electron neutrinos get converted into the other types and are not detected in the solar neutrino experiments. -> discrepancy between theory and observations.

Stellar evolution

- A main-sequence star is expected to generate energy steadily as long as hydrogen in the core is converted into helium. The luminosity or the surface temperature of the star does not change much during this phase when it lies on the main sequence.
- **Eventually, the hydrogen in the core of the star is exhausted. What then happens to the star? This is the central question of stellar evolution.**
- The only way of answering this question is through very detailed numerical computations.
- The picture which emerges from these computations is quite complicated in its details. A star evolves through many very different stages. Also, stars of different masses evolve very differently.
- We will discuss the basic ideas her.

Stellar evolution

Once hydrogen is exhausted in the stellar core, not enough energy is generated there to balance the inward pull of gravity. As a result, the core of the star starts shrinking and the gravitational potential energy released in the process generates heat -> the core gets hotter in this process. This has two important consequences:

- (1) **Heavier elements undergo nuclear fusion at higher temperatures,** since a stronger Coulomb barrier has to be overcome. When the core becomes sufficiently hot, helium starts burning to produce carbon, halting the Kelvin–Helmholtz contraction.
- **When helium is exhausted, the same cycle repeats, until the core becomes hot enough for the next nuclear fuel to burn.**
- Very massive stars go through a complicated phase when different nuclear fuels burn in different spherical shells of the star with different temperatures.
- In very heavy stars, the core eventually ends up being iron, which has the most strongly bound nuclei.
- On the other hand, **for light stars, the core temperature may never become high enough** (before the electron degeneracy pressure halts the gravitational contraction) **even for helium burning**, so that the core remains a helium core.

Stellar evolution

- (2) The **excess heat** produced in the Kelvin–Helmholtz contraction of the core **inflates the outer layers of the star.**
- Hence the star can bloat up to a **huge size, while its luminosity does not change** that much, so that its **surface temperature drops.**
- This causes the position of the star in the HR diagram to move away from the main sequence and follow the trajectory shown in Figure 4.9. Thus the star ends up being a **red giant.**
- The **position of the star in the HR diagram changes whenever a new nuclear fuel is ignited** in the core of the star.

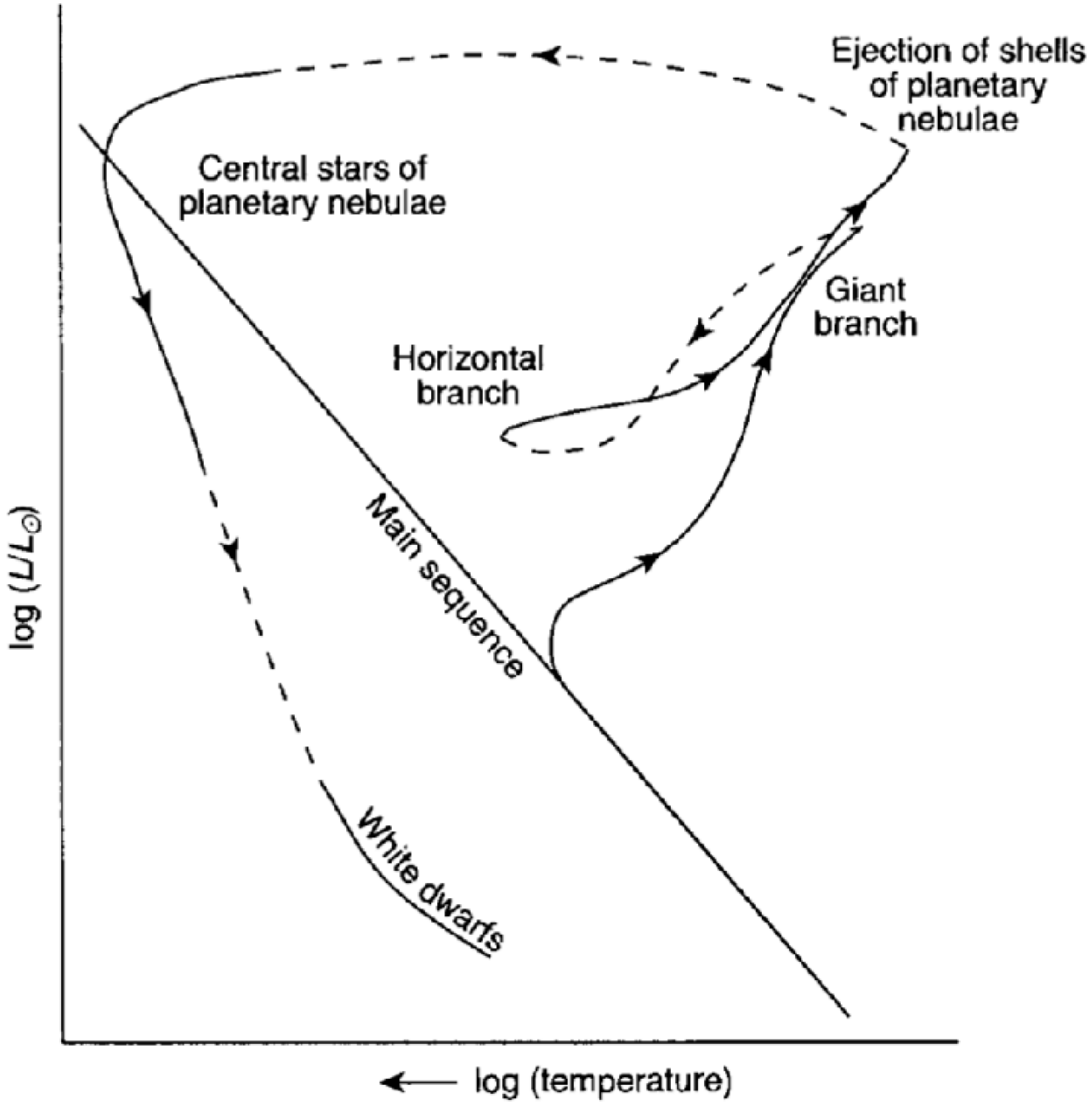


Fig. 4.9 A schematic trajectory of a star in the HR diagram. From Longair (1994, p. 31), after a figure of Mihalas and Binney (1981).

Stellar evolution

- Figure shows **theoretical trajectories of stars of different masses** based on detailed computations.
- Whenever a new nuclear fuel is ignited, there is a tendency of the trajectory proceeding back towards the main sequence.
- Eventually all nuclear fuels in the core that could be ignited at the prevailing conditions are exhausted and no more nuclear energy is produced to halt the gravitational contraction.
- If the **mass of the core is less than a critical mass**, then **gravity inside it can be balanced by electron degeneracy pressure** when the density rises to sufficiently high values.

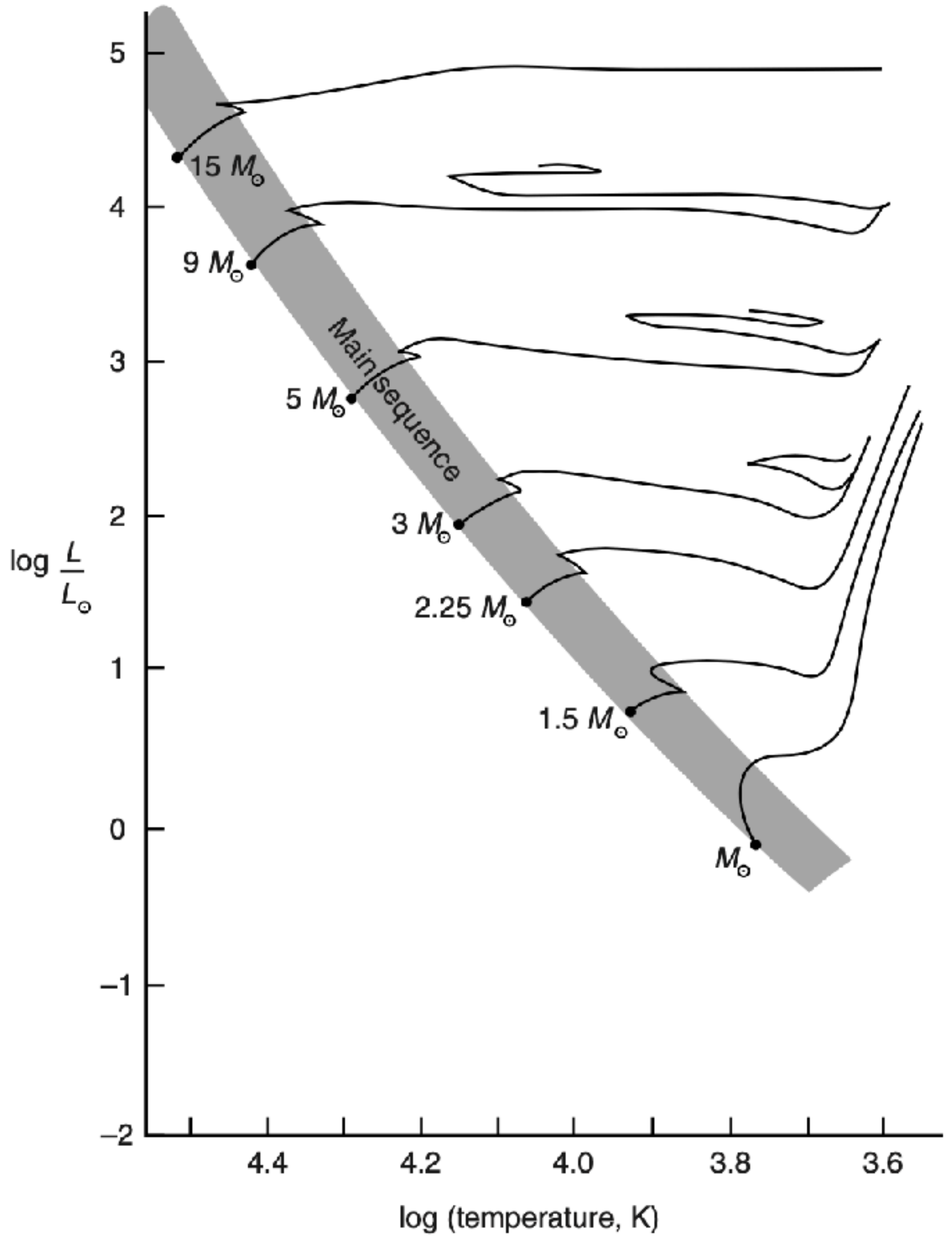


Fig. 4.10 Theoretical trajectories in HR diagram of stars of different masses, based on detailed computations. From Longair (1994, p. 33), after a figure of Mihalas and Binney (1981).

Stellar evolution

- The **core stops shrinking** and the bloated **envelope of the star gets removed.**
- There are **various mass loss mechanisms** by which a large part of the outer envelope may be lost – either steadily or more violently.
- Any remaining part of the envelope may again settle on the core, so that we finally may have a compact star, which has a hot white surface initially and then gradually cools.
- Figure shows the trajectory of the star as it evolves to become a **white dwarf**.
- Most stellar evolution codes fail to predict very reliable trajectories in the HR diagram in this phase, because many aspects of the theory are still under investigation.

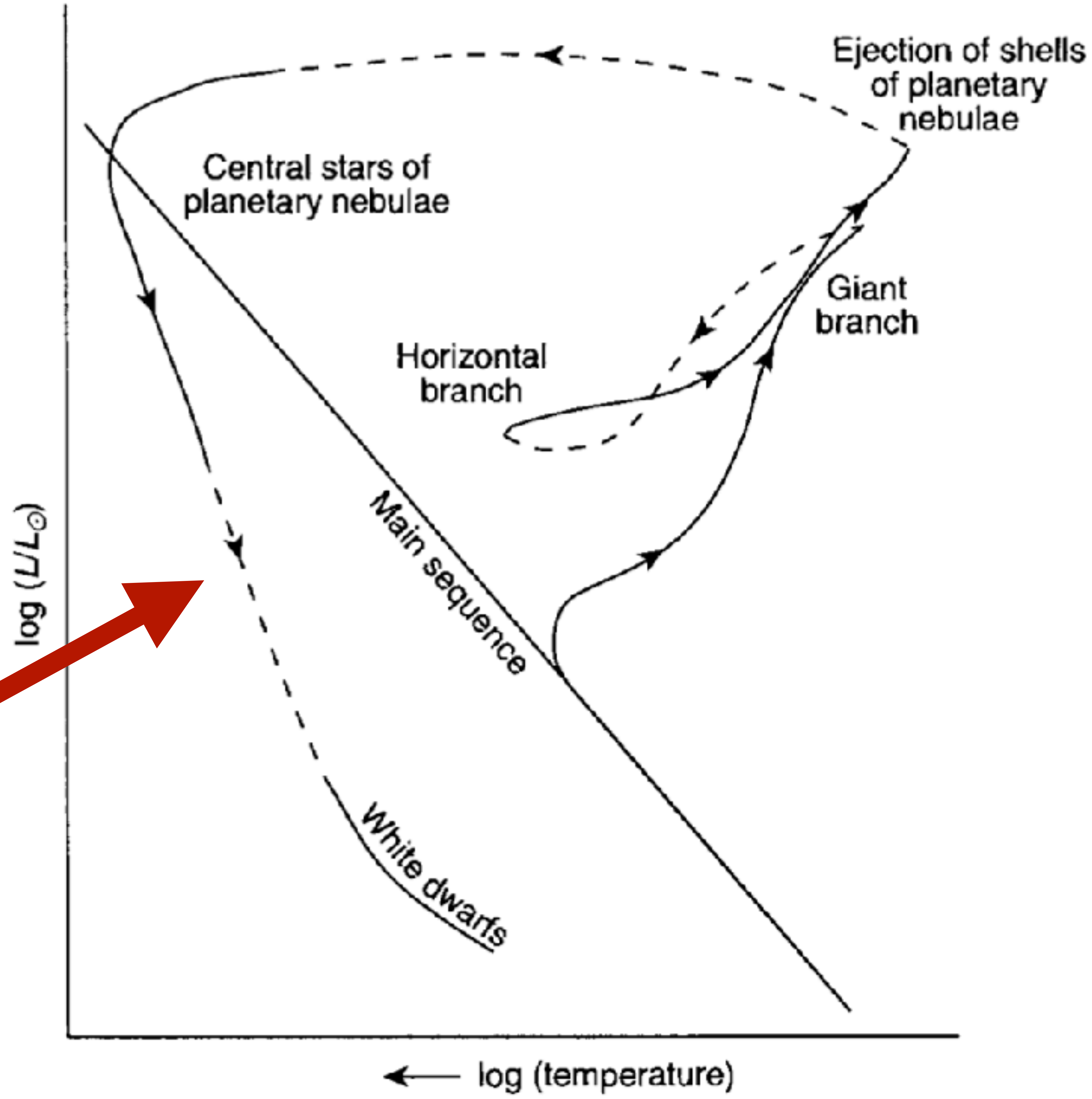
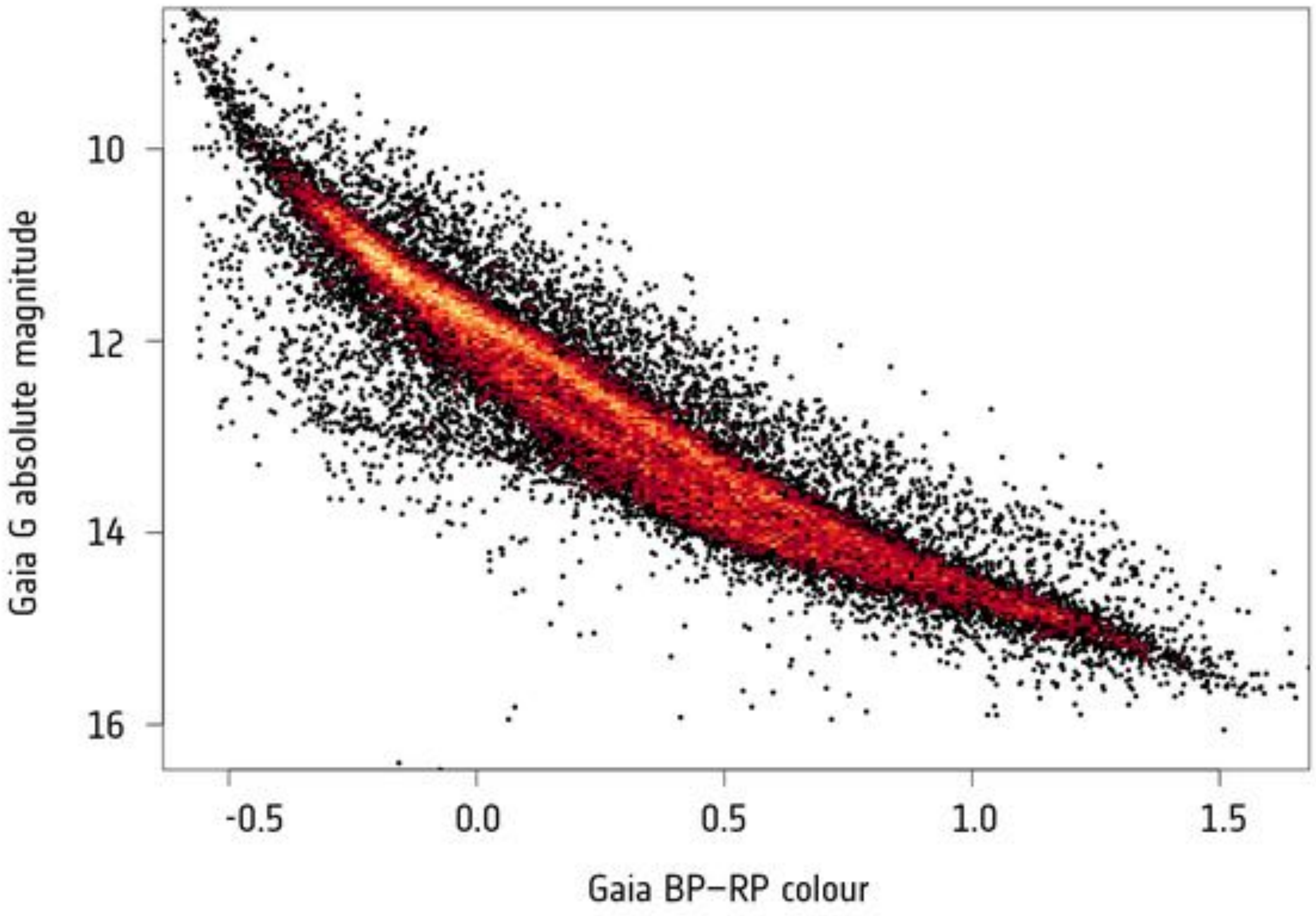


Fig. 4.9 A schematic trajectory of a star in the HR diagram. From Longair (1994, p. 31), after a figure of Mihalas and Binney (1981).

Stellar evolution

- The **mass limit of white dwarfs is about $1.4 M_{\odot}$.**
- However, more massive stars also eventually may end up as white dwarfs by losing a large part of the mass.
- **If the final mass remains larger than $1.4 M_{\odot}$,** then the other possible final configurations are **neutron stars and black holes**.



Zoom in on the white dwarfs in the H-R diagram based on GAIA data. The two roughly parallel yellow lines within the broader strip are likely an imprint of two different types of white dwarfs, those that have hydrogen-rich atmospheres and those that are dominated by helium.

https://sci.esa.int/web/gaia/-/60209-white-dwarfs-in-gaia-s-hertzsprung-russell-diagram

Evolution in a binary system

- What is a binary system?

Evolution in a binary system

- A large fraction of stars are estimated to be in binary systems.
- **If it is a close binary with the two stars very near each other,** then their **evolution can differ** in important ways from the evolution of isolated stars.
- The two stars in a binary system **revolve around their common centre of mass**, with an angular velocity denoted by Ω. In a frame of reference rotating with Ω, the two stars will be at rest. The force acting on a particle at rest in this frame will be the **gravitational attractions of the two stars plus the centrifugal force.** The effective potential will be given by

$$\Phi = -\frac{GM_1}{r_1} - \frac{GM_2}{r_2} - \frac{1}{2}\Omega^2 s^2$$

where r_1 and r_2 are the distances of the particle from the centres of the two stars, whereas s is the distance from the rotation axis passing through the centre of mass.

Evolution in a binary system

- The Figure shows some of the **equipotential surfaces** in a typical case.
- **The surface of a star should be an equipotential surface**, if we want to ensure that there are no unbalanced horizontal forces at the stellar surface. Each of the stars should extend up to some equipotential surface.

- The equipotential surfaces near any one of the stars go around that star alone.
- On the other hand, the equipotential surfaces far away surround both stars.
- There is a **critical surface made with the equipotential surfaces around the two stars touching at a point L**. This point is called the ***inner Lagrange point***, whereas the **critical surface is known as the *Roche lobe***.

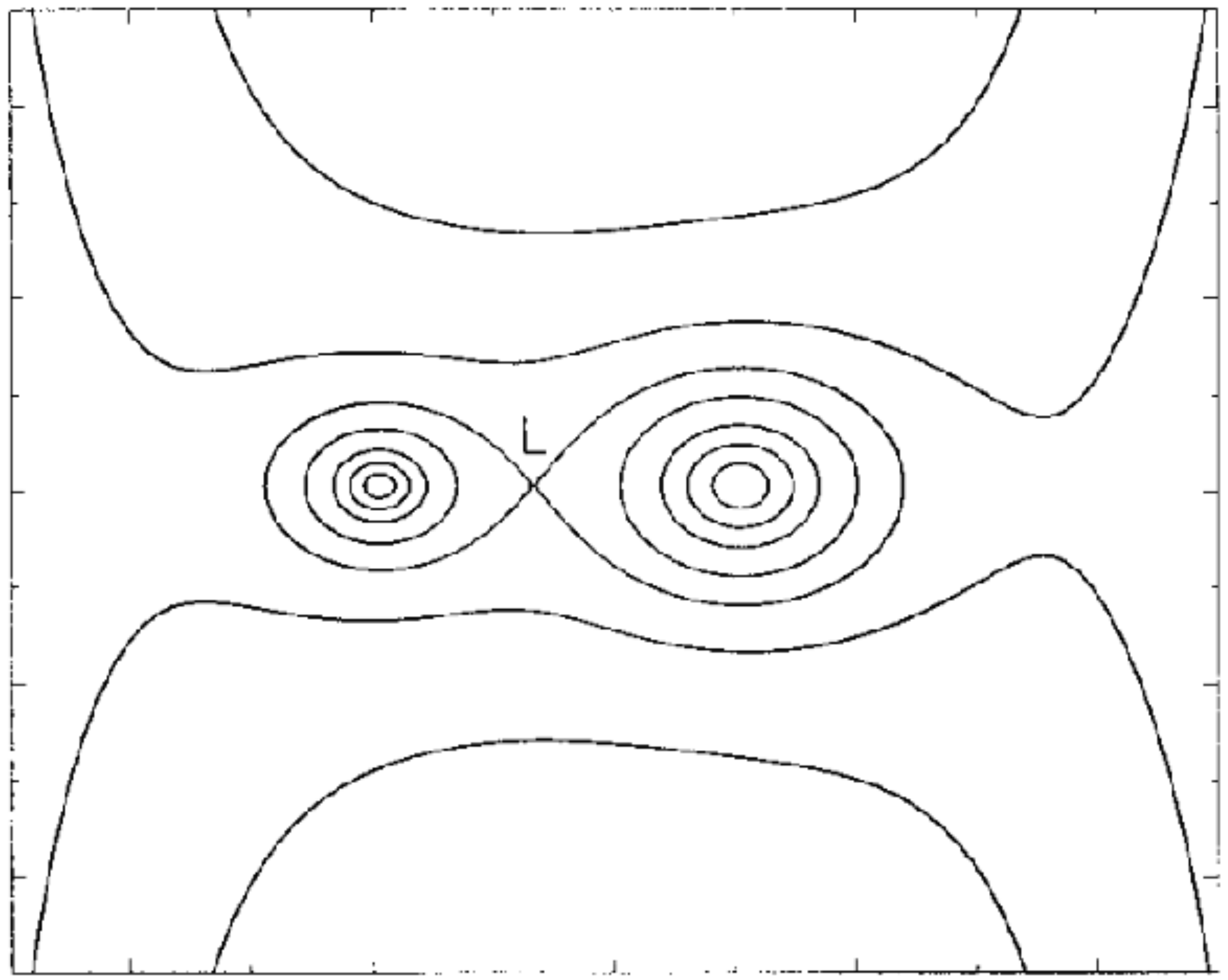
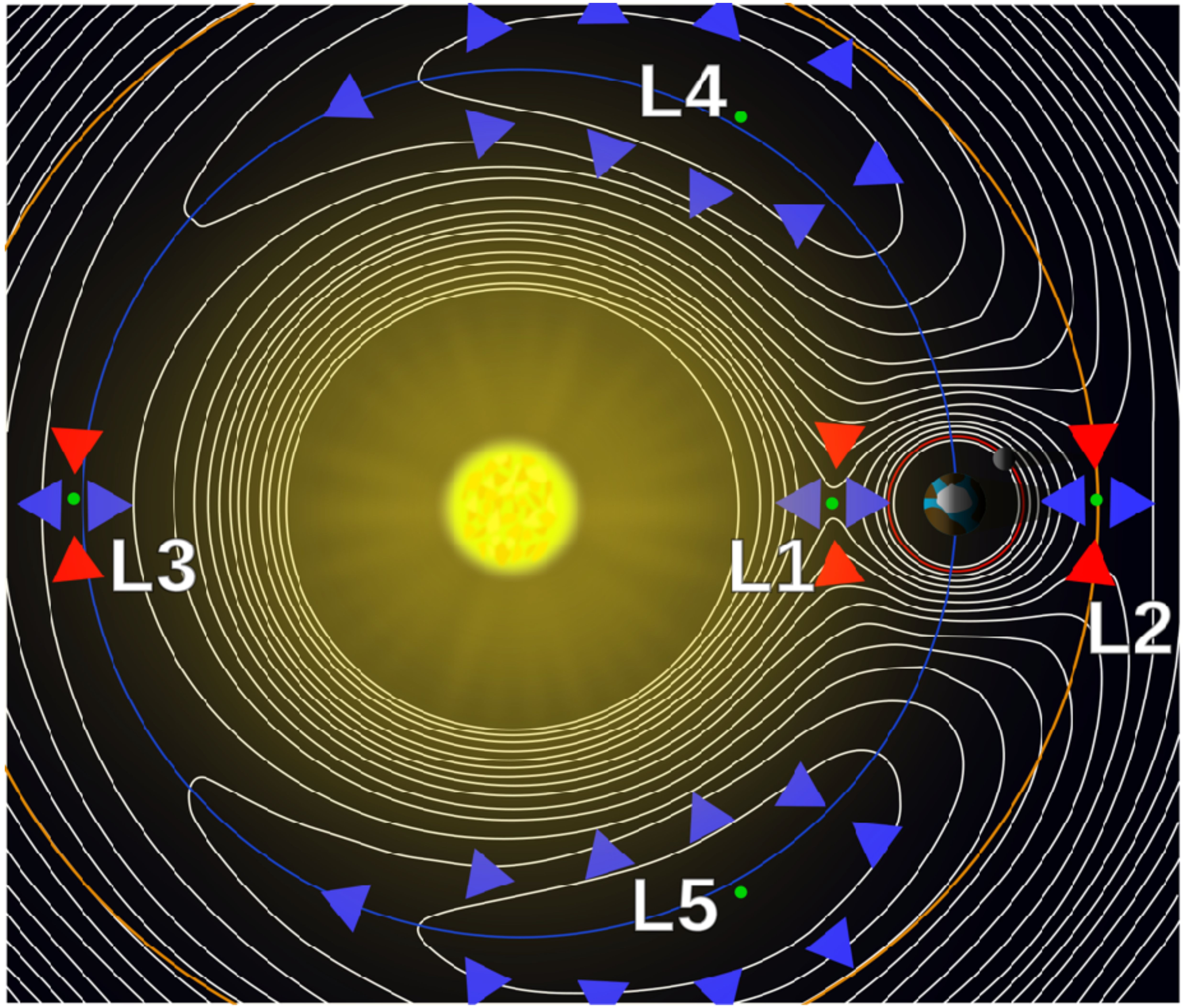


Fig. 4.11 Equipotential surfaces of two stars rotating around a common centre of mass, in the rotating frame of reference.

Evolution in a binary system

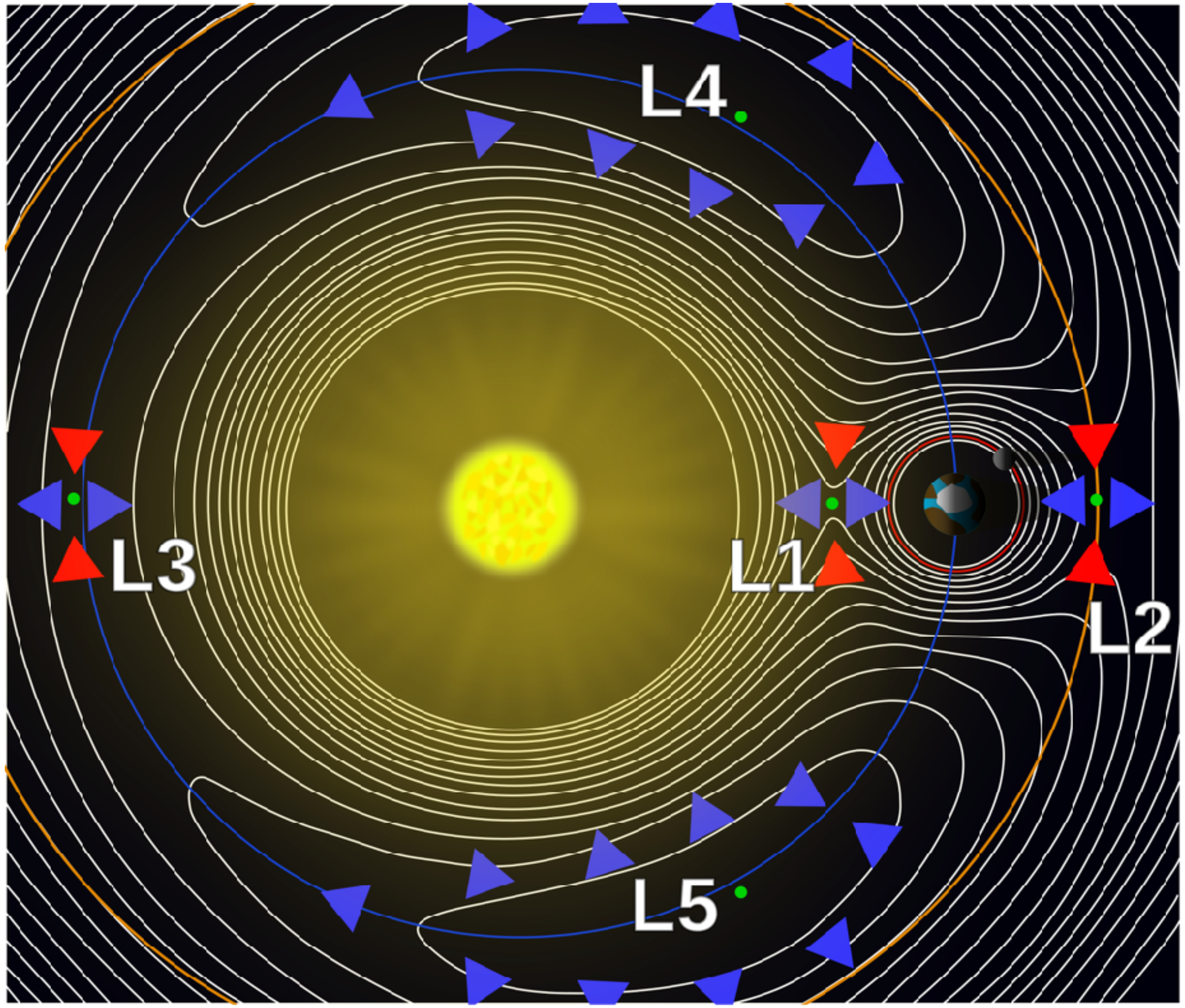
- In celestial mechanics, the **Lagrange** or libration **points are points of equilibrium for small-mass objects** under the influence of two massive orbiting bodies.
- For any combination of two orbital bodies there are five Lagrange points, L_1 to L_5, all in the orbital plane of the two large bodies.
- A contour plot of the effective potential due to gravity and the centrifugal force of a two-body system in a rotating frame of reference.
- The arrows indicate the downhill gradients of the potential around the **five Lagrange points**, toward them (red) and away from them (blue).
- The L_4 and L_5 points are the high points of the potential. At the points themselves these forces are balanced.



https://en.wikipedia.org/wiki/Lagrange_point

Evolution in a binary system

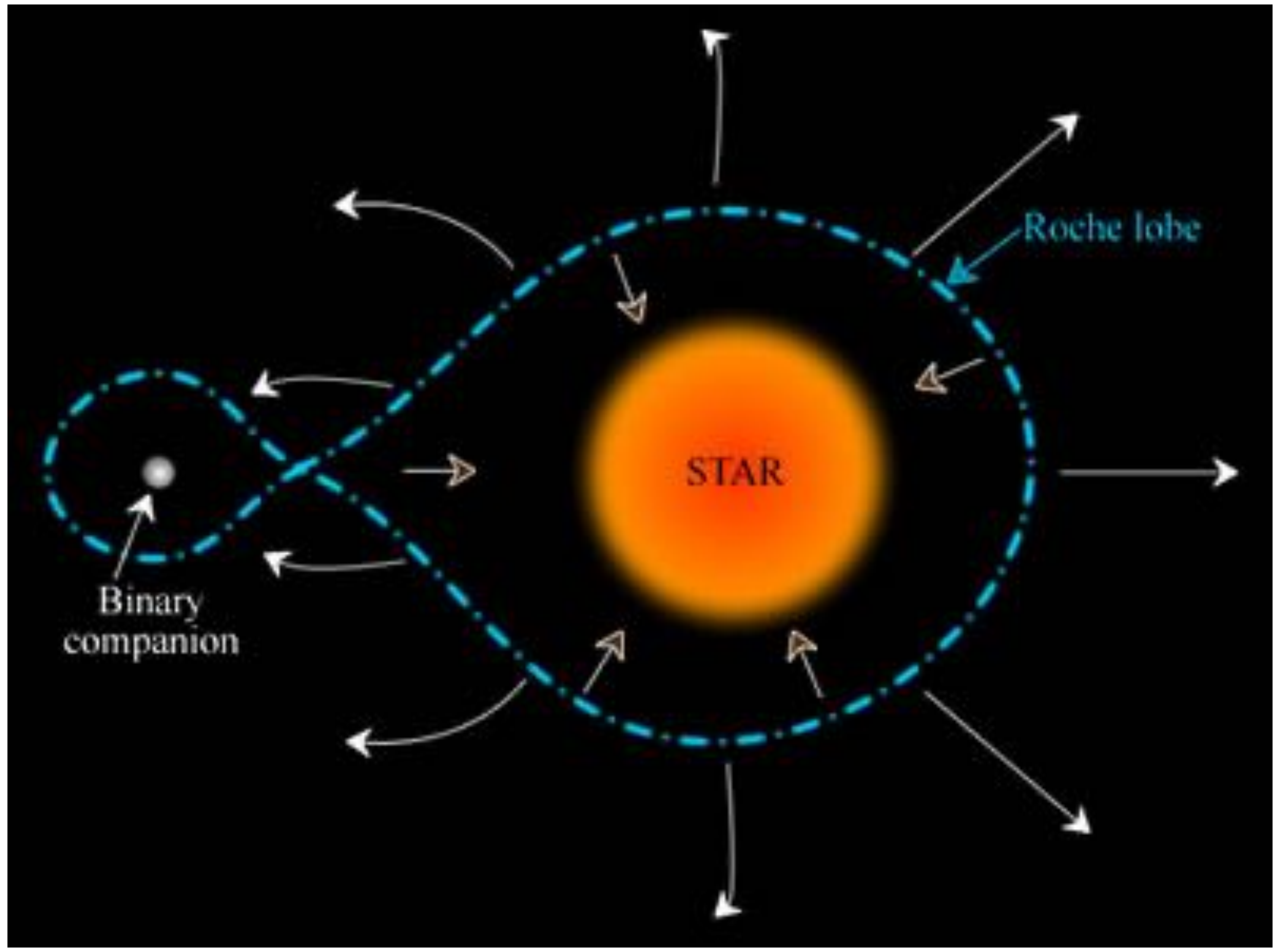
- When the mass ratio of the two bodies is large enough, the L_4 **and** L_5 **points** are stable points meaning that objects can orbit them, and that they have a tendency to **pull objects into them**.
  - Several planets have **trojan asteroids** near their L_4 and L_5 points with respect to the Sun; Jupiter has more than one million of these trojans.
- Two important Lagrange points in the Sun-Earth system are L_1, which is located between the Sun and Earth, and L_2, which is beyond the Moon.
  - **The James Webb Space Telescope**, a powerful space observatory, **is located at** L_2**.** This allows to protect the telescope from the light and heat of the Sun and Earth (and Moon).

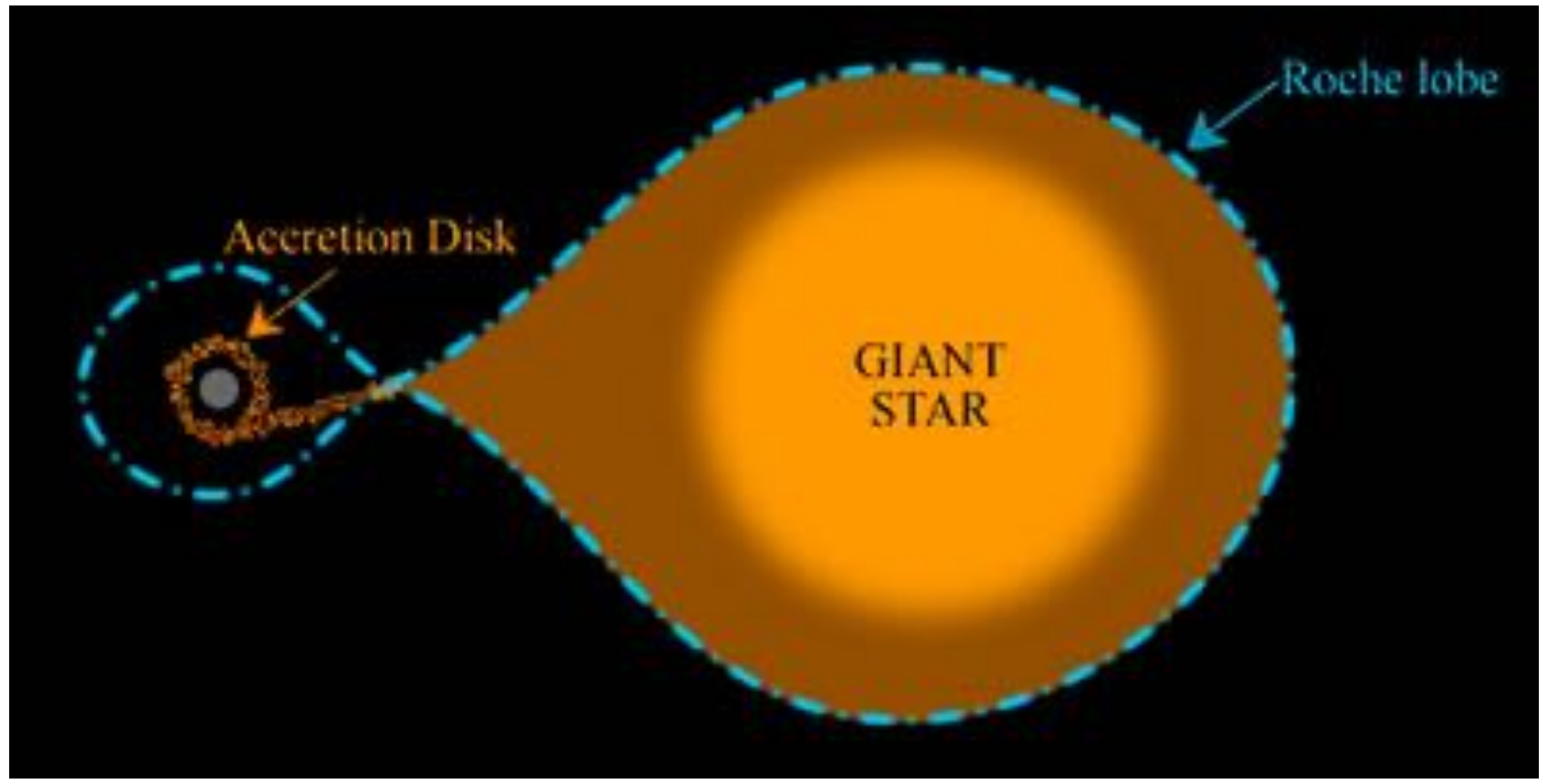


https://en.wikipedia.org/wiki/Lagrange_point

Evolution in a binary system

- When **one of the stars becomes a red giant,** its surface may **bloat up to the Roche lobe**, after which the **gas from the surface should start falling into the other star through the inner Lagrange point.**
- Such a mass transfer can lead to varieties of complicated situations.
- The more massive star of the binary finishes its life on the main sequence first and becomes a red giant.
- If it succeeds in **transferring a significant amount of mass to the other star, then this other star may become more massive and may start evolving faster.**





https://astronomy.swin.edu.au/cosmos/r/roche-lobe

Mass loss from stars - Stellar winds

- When a star becomes a red giant, **the gravitational attraction at its inflated surface becomes much smaller** than that at an ordinary stellar surface.
- This reduces the star's ability to hold on to the material on its surface and the **surface material may keep escaping**.
- Even in the case of an **ordinary star** like the Sun, **material is continuously escaping** from its corona in the form of a flow known as the ***solar wind*.**

Stellar wind from the star L.L. Orionis generating a bow shock (the bright Arc)

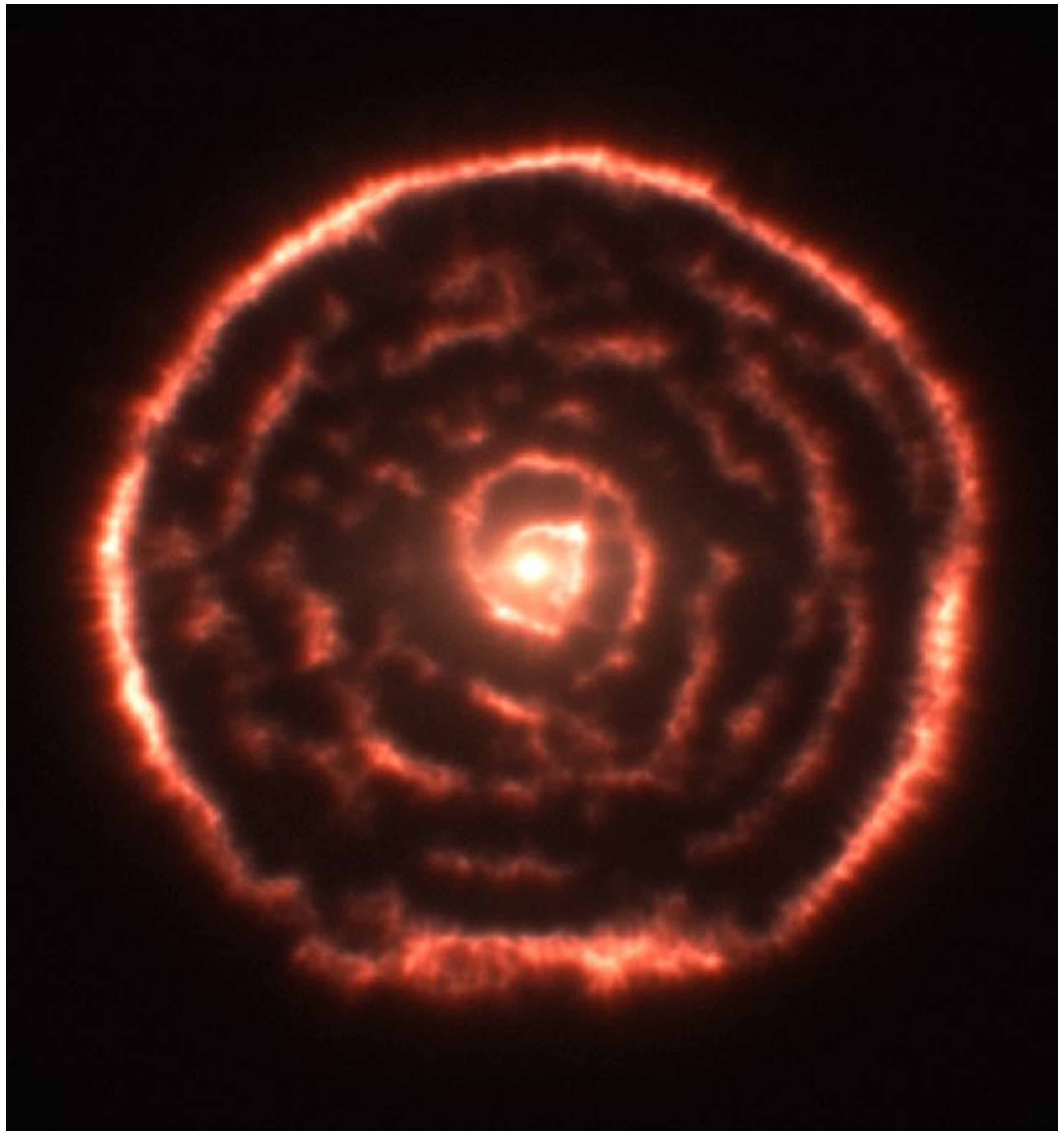
Mass loss from stars - Stellar winds

- Although the temperature of the solar surface is about 6000 K, the corona has a much higher temperature of the order of a million degrees.
- Before the discovery of the solar wind, the corona was believed to be in static equilibrium.
- However, based on models the hot solar corona could be in static equilibrium only if some appropriate pressure is applied at infinity to stop it from expanding.
- Since there is nothing to contain the corona by applying the necessary pressure, Parker (1958) **suggested that the outer parts of the corona must be expanding in the form of solar wind.**
- The solar wind was detected from spacecraft observations just a few years after Parker's prediction.
- The solar wind is an example for a **thermally driven wind.** It is caused by the high temperature of the corona, which makes it difficult for gravity to hold on to the gas.

Stellar wind from the star L.L. Orionis generating a bow shock (the bright Arc)

Mass loss from stars - Stellar winds

- There are other mechanisms of driving winds.
- The radiation force in the outer atmosphere of a very massive star may become comparable to gravity. This may cause a **radiatively driven wind.**
- If a star is rotating very fast, that may lead to a **centrifugally driven wind.**
- The Sun loses only about $10^{-14}\ M_\odot\ \mathrm{yr}^{-1}$ due to the solar wind.
- Because of the weak gravity at the surface of a red giant, **often red giants have much stronger winds.** It is possible for a star to lose a significant fraction of its mass while passing through the red giant phase.



silicates around R Sculptoris
(asymptotic giant branch star)

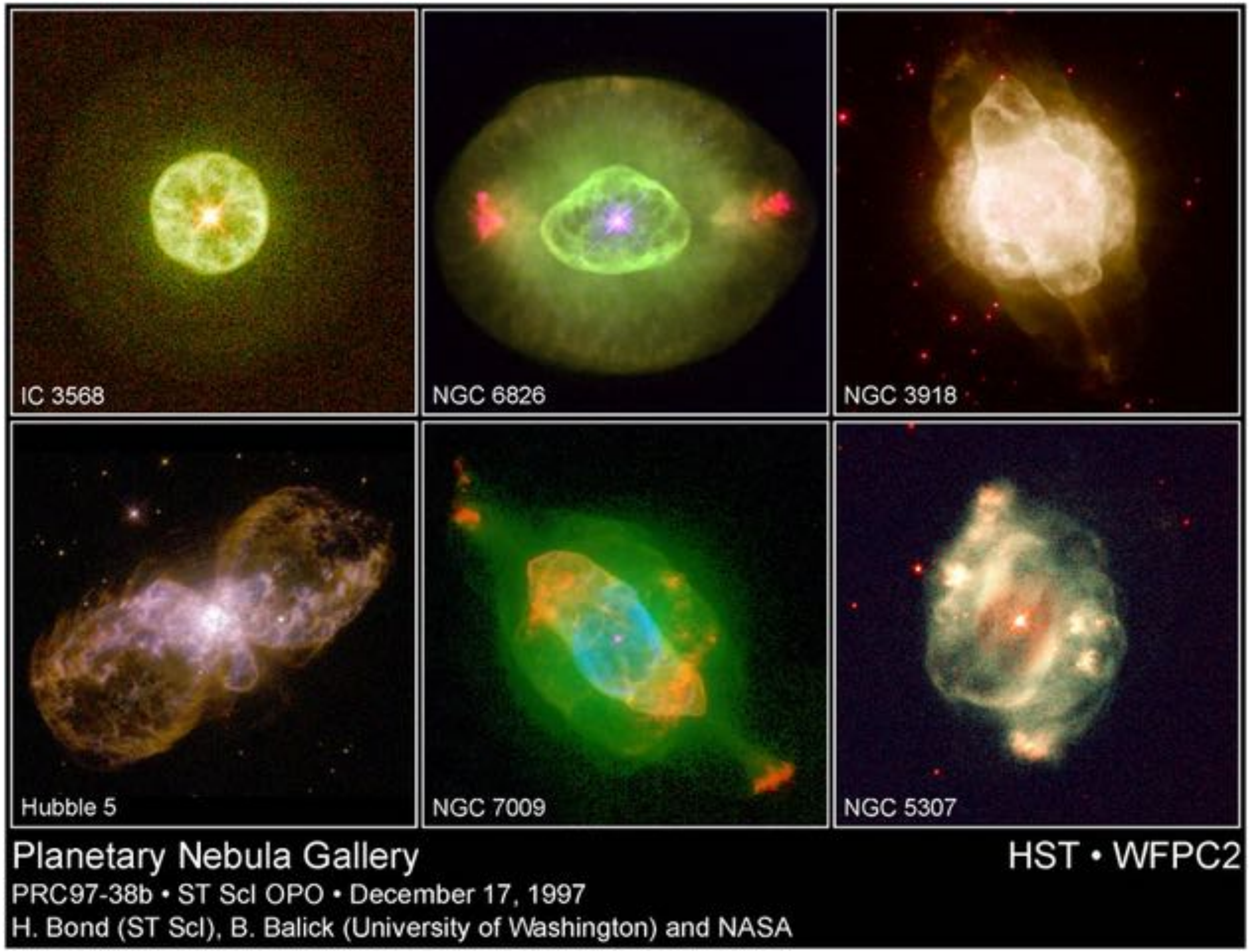
Mass loss from stars - Stellar winds

- A dramatic confirmation of mass loss comes from the observations of what are called ***planetary nebulae*.**
- *Through the low-resolution telescopes of earlier times, a planetary nebula looked somewhat like a planet.*
- We now know that a planetary nebula is essentially **the outer shell of a star which has been blown off.**
- At the **centre of a planetary nebula, we usually find the hot core** of the star, which is eventually expected to **become a white dwarf.**

Planetary nebula: NGC 7293, the Helix Nebula.

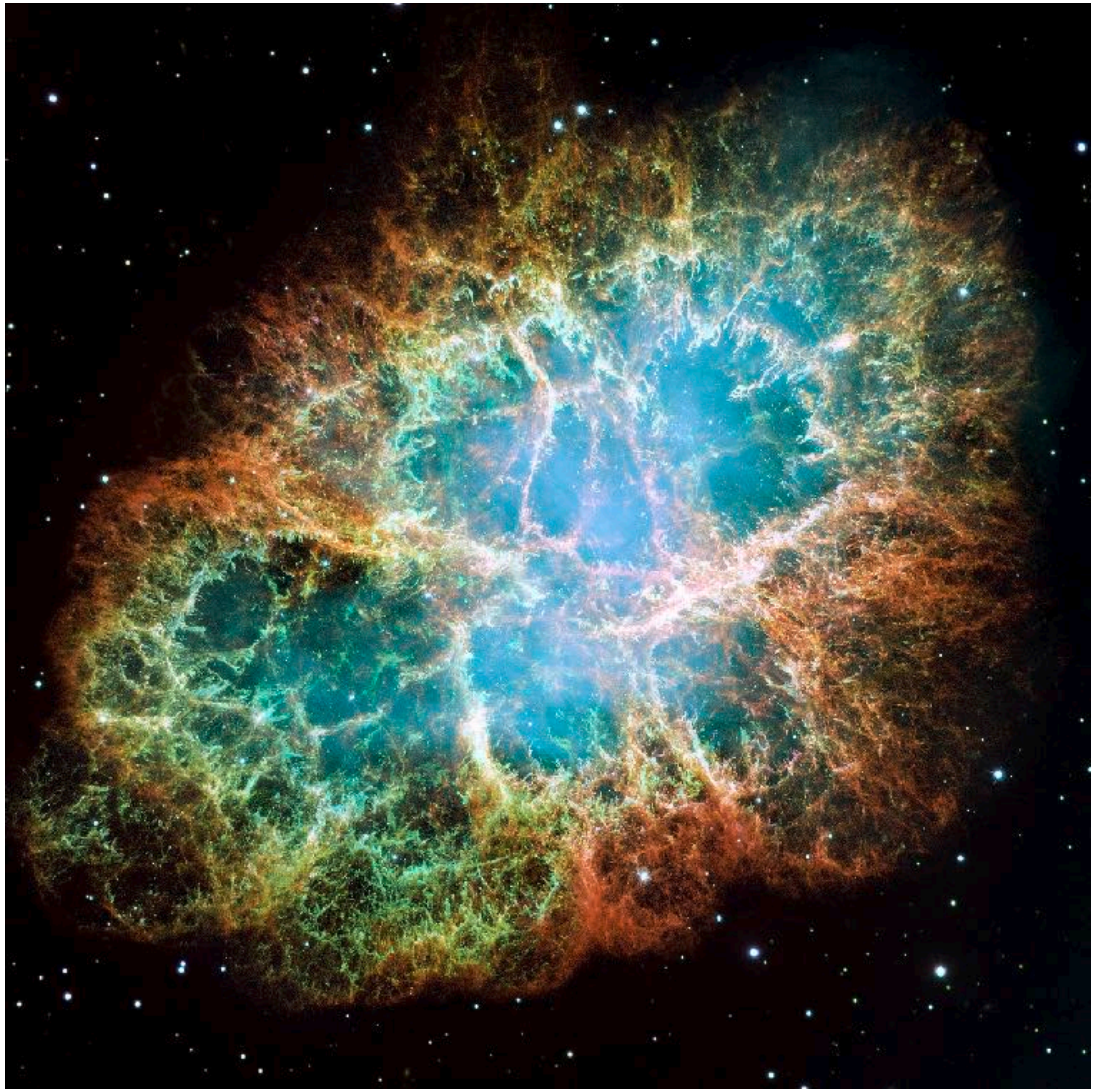
Mass loss from stars - Stellar winds

- Planetary nebulae can have many different shapes



Supernovae

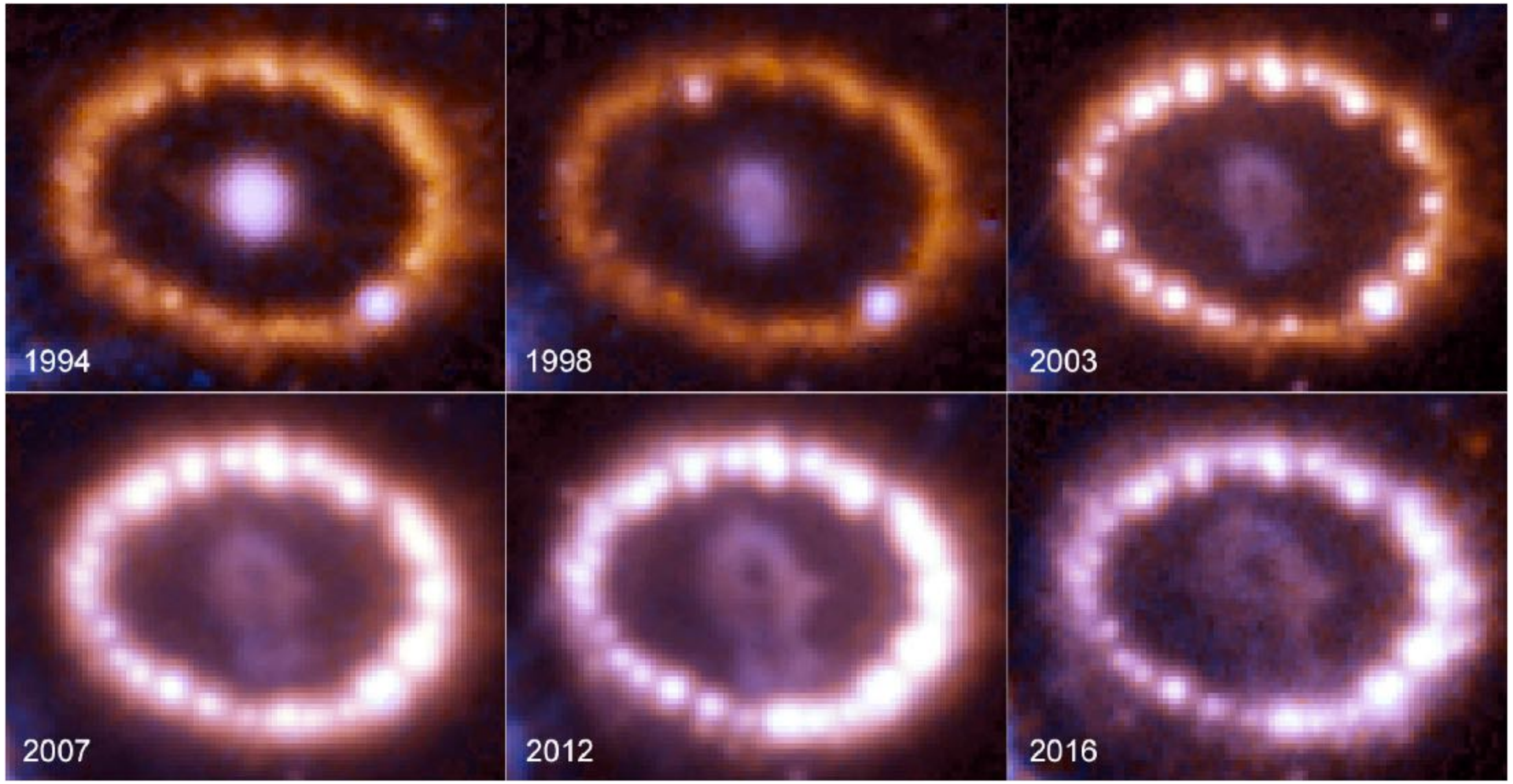
- Chinese astronomers recorded that in the year **1054 a star** in the Taurus constellation **became so bright that it was visible during daytime**. Figure shows what a modern telescope finds in that spot of the sky.
- We see a **luminous gas shell, known as the Crab Nebula** because of its crab-like appearance.
- By comparing photographs taken at intervals of a few years, one easily finds that **the shell is increasing in size** and a simple backward extrapolation suggests that this shell must have started from a very small size around 1054.
- Presumably, what the Chinese astronomers recorded was the explosion of a star which created today's Crab Nebula.



Hubble Space Telescope image of the Crab Nebula

Supernovae

- Statistical **estimates suggest that there should be about 30 such supernova explosions in our Galaxy in every 1000 years.**
  - However, we are able to see only a very small fraction of our Galaxy in visible light.
- Tycho and Kepler carefully studied two supernovae in our Galaxy seen in the years 1572 and 1604 respectively. No supernova has been observed in our Galaxy after the invention of the telescope!



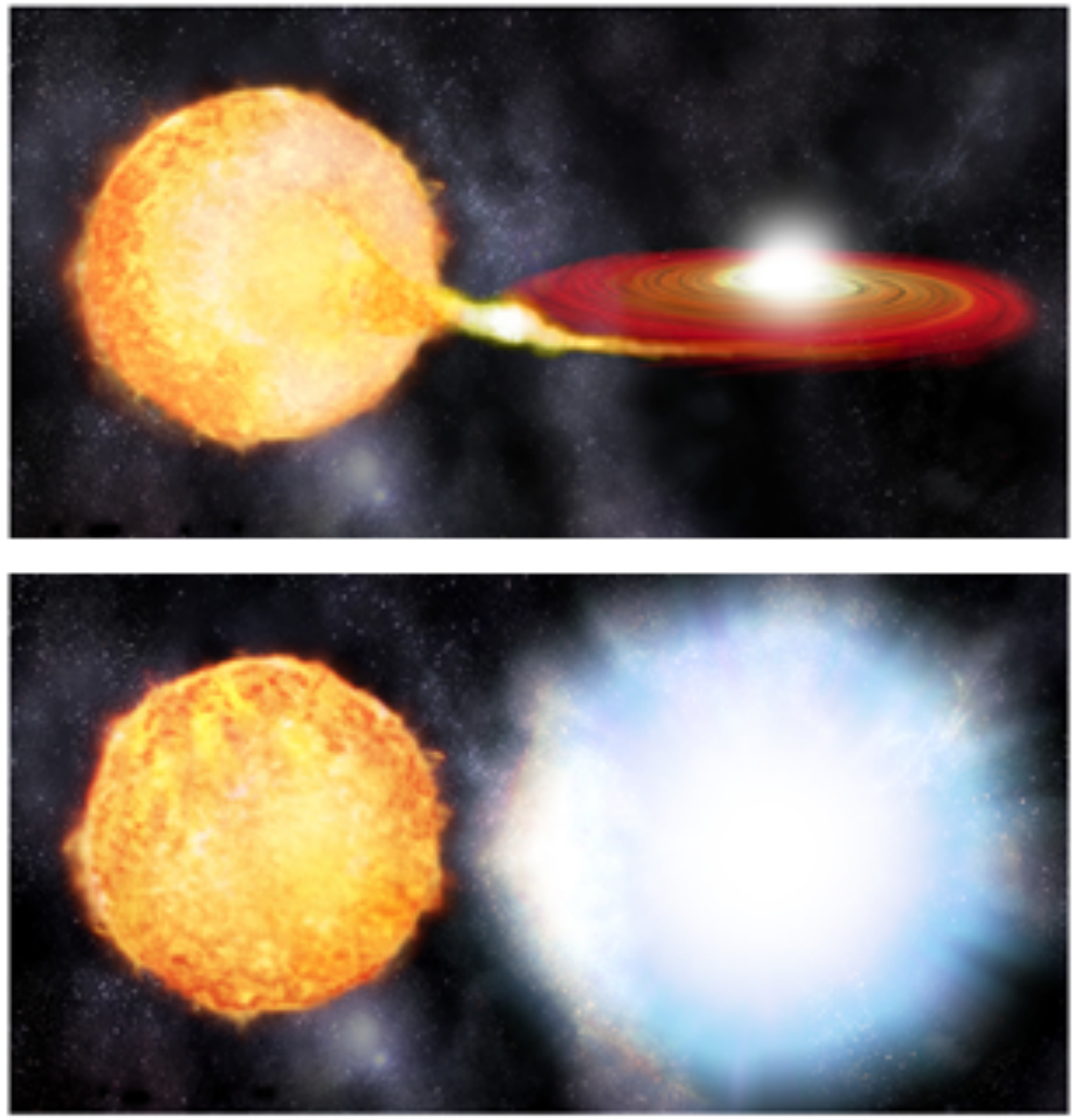
- The supernova seen in 1987, was in the **Large Magellanic Cloud**, which is a companion to our Galaxy at a distance of about 55 kpc. Called **SN 1987A**, is on of the most studied **supernova remnants.**
- The energy involved in a typical supernova explosion is estimated to be about 10^{45} J.

Supernovae

- By studying many supernovae, astronomers have concluded that supernovae can be divided into two types:
  - **Type I** supernovae and
  - **Type II** supernovae, which have different characteristics.
- These two classes are divided into some subclasses.
- Amongst Type I supernovae, the most interesting ones are Type Ia. All **Type Ia supernovae appear almost identical.** They reach exactly the same maximum intrinsic luminosity and afterwards their luminosities also decrease in exactly the same way.
- On the other hand, the Type II supernovae show some variations from one supernova to the other.

Supernovae Type Ia

- Why are they identical?
- If a white dwarf is in a close binary system. When its companion becomes a red giant, it is possible for a mass transfer to take place onto the white dwarf. The maximum mass which a white dwarf can have is the Chandrasekhar mass of about $1.4M_{\odot}$, beyond which it is not possible for electron degeneracy pressure to balance gravity.
- Suppose the **mass transfer increases the mass of the white dwarf just beyond the Chandrasekhar mass**. Then gravity cannot be balanced any more and the white dwarf star may have a catastrophic explosion, which probably disrupts the star completely without leaving any remnant behind.
- If all the Type Ia supernovae are produced in this way, by the **explosions of white dwarfs of identical mass under identical conditions, then it is certainly expected that all these supernovae should appear identical -> same luminosity -> distance measurement**



Supernovae Type II

- **Type II supernovae** are believed to take place in **much more massive stars.**
- This is inferred from the fact that they usually take place in regions where star formation has taken place recently and massive stars, which are short-lived, are found only in such regions.
- When the core of the massive star completely runs out of all nuclear fuels, it starts shrinking until the core density becomes comparable to the density inside an atomic nucleus ($\approx 10^{17}$kg m^{-3}). The neutron degeneracy pressure may balance gravity at such densities.
- When this happens, the rapidly shrinking core suddenly stops shrinking any more. The surrounding material falling inward with the core gets bounced back when the collapse of the core is suddenly halted. **The Type II supernova is caused by the explosive bouncing off of the envelope surrounding the newly formed neutron star core.**

Supernovae Type II

- The **variation of the supernova luminosity with time** is called its ***light curve***.
- The shape of the light curve can be used to **identify the type** of the supernovas.
- Figure shows the light curve of **SN 1987A**, which was a **Type II** supernova.
- A large portion of the light curve appears like an exponential decay (vertical axis in Figure is logarithmic) with a half-life of about 77 days.
- Now ^{56}Co, which is a radioactive isotope of cobalt, decays into ^{56}Fe with a half-life of 77.1 days.
- It is believed that copious amounts of ^{56}Co are produced in a Type II supernova and it is the decay of this which is responsible for the light curve.

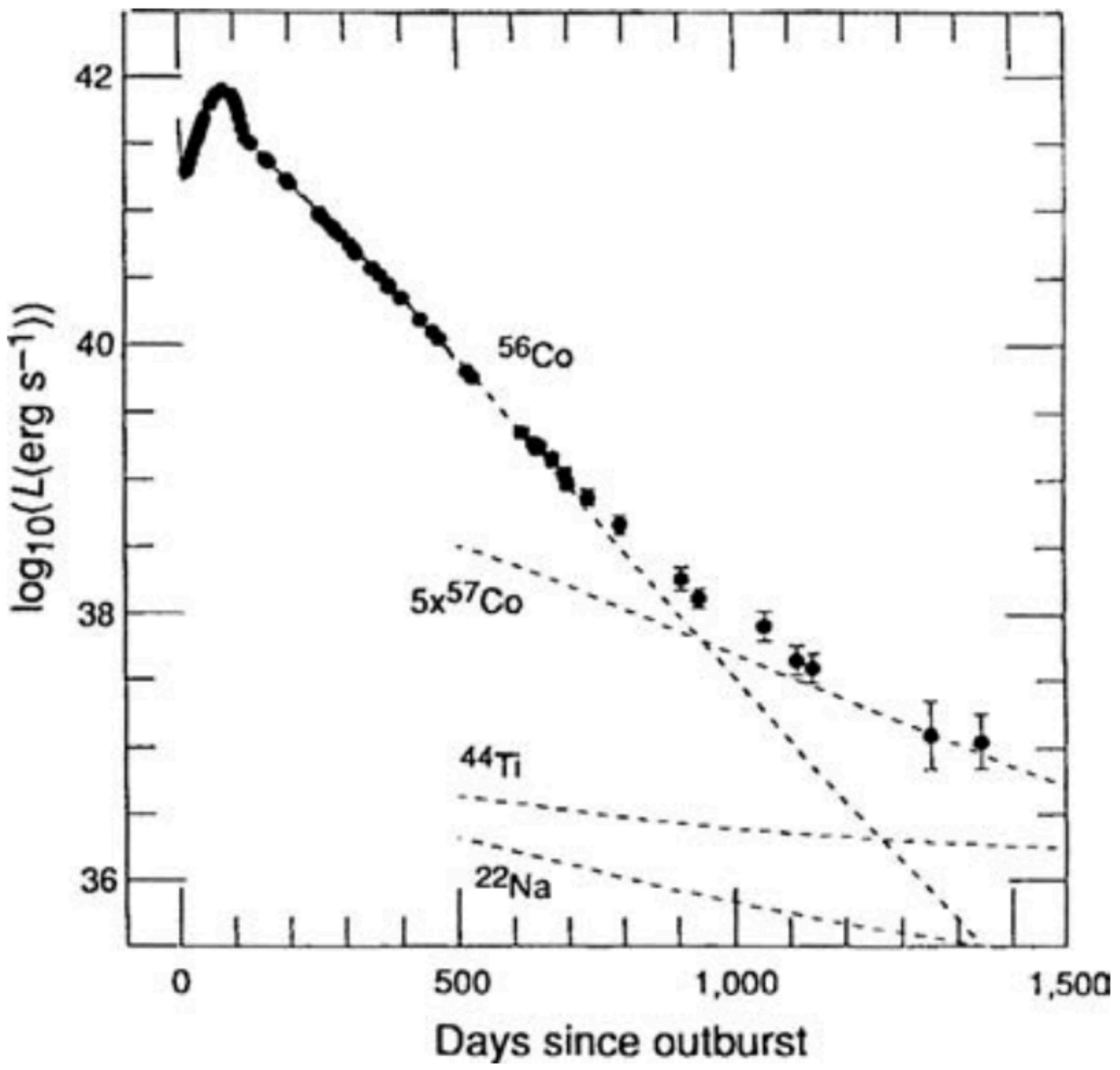


Fig. 4.14 The light curve of SN 1987A. The dashed lines indicate how the number densities of the radioactively decaying nuclei ^{56}Co and ^{57}Co would decline with time. From Chevalier (1992). (©Nature Publishing Group. Reproduced with permission from *Nature*.)

Supernovae Type II

- Nuclear reactions in the interiors of very massive stars may convert the core into iron, which is the maximally bound nucleus, so that no more nuclear burning is possible after its formation.
- **How are the heavier elements produced then?**
- Elements heavier than iron are synthesized in Type II supernovae
- It is possible for an electron and a proton to combine to form a neutron:

$$\boxed{p + e^- \rightarrow n + \nu.}$$

- However, since the **mass of a neutron is more than the combined mass of a proton and an electron**, this reaction cannot proceed **unless some extra energy is supplied.**
- In a **supernova explosion, electrons** suddenly **become highly energetic** and it becomes possible for the above reaction to proceed, producing large numbers of neutrons and neutrinos.

Supernovae Type II

$$n \rightarrow p + e^- + \bar{\nu}_e.$$

- Considering a nucleus of mass A and charge Z.
- The **electrostatic repulsion of a heavy nucleus is much stronger than that of a light nucleus**. So another charged particle cannot easily come near the heavy nucleus.
- But the **uncharged neutron can come close and get absorbed** by it, increasing the mass of the nucleus to $A + 1$. This process is called **neutron capture.**
- It is well known that **nuclei too massive for their charge Z tend to be unstable to β-decay**. If the nucleus emits a β-particle, we end up with a nucleus of mass $A + 1$ and charge $Z + 1$ starting from a nucleus of mass A and charge Z .
- **Heavier nuclei can be built up in this way.**
- Our solar system has many elements heavier than iron which, could only be synthesized in a supernova. Presumably there was a very massive star in our neighbourhood before the solar system formed. This massive star must have ended its life in a supernova and the debris of this supernova with heavy elements got mixed with interstellar gas, out of which the solar system formed.

Supernovae Type II

$n \rightarrow p + e^- + \bar{\nu}_e.$

- Many neutrinos should be produced by reaction when the core collapses violently to trigger a Type II supernova.
- Evidence for this was found when **20 neutrinos from SN 1987A were detected** by two experiments – one of them being Kamiokande.
- The flux estimated from these neutrinos suggests that a very **major portion of the gravitational potential energy lost** (in the core collapse to produce a neutron star) **must be carried away by the neutrinos.**
- **The arrival times of the neutrinos were spread over 12 s**. If all the neutrinos were emitted at the same time and had zero mass, then they would have all travelled at speed *c* and should have arrived simultaneously.
- On the other hand, if the neutrinos had mass, then the less energetic neutrinos would have travelled slightly slower and one gets an **upper bound of 20 eV for the neutrino mass** from the observed spread in arrival times. This is an upper bound, since it is possible that the neutrinos were emitted at slightly different times and then travelled at the same speed.

Stellar rotation and magnetic fields

- In our discussion of stellar structure, we have assumed spherical symmetry.
- There are two factors which could cause departures from spherical symmetry of a star – rotation and magnetic field.
- We know quite a lot about the rotation and magnetic field of our nearest star – the Sun.
- For normal stars, the effect of rotation or magnetic field is usually not enough to cause appreciable departures from spherical symmetry, which is the case for the Sun. Even when stellar rotation or the stellar magnetic field may not be important from the point of view of stellar structure, they are certainly intriguing astrophysical effects which can have many other consequences.

Solar rotation

- It was known for a long time that the Sun does not rotate like a solid body. **The equator of the Sun rotates faster than the pole**, taking about 25 days to go around the rotation axis, whereas a point near the pole would take more than 30 days to go around.
- It is possible to map the **distribution of angular velocity in the interior of the Sun with the help of helioseismology.** We basically **measure the eigenfrequencies of many modes of oscillation in the Sun.** Because of the spherical geometry, we expect that the velocity associated with a normal mode must be of the form

$$\mathbf{v}(t, r, \theta, \phi) = \exp(-i\, \omega_{nlm} t)\, \xi_{nlm}(r) Y_{lm}(\theta, \phi),$$

where $Y_{lm}(\theta,\phi)$ is a spherical harmonic. If the Sun were non-rotating, it can be shown that ω_{nlm} would be independent of m. In other words, the eigenfunctions with the same n and l, but different m, would have the same frequencies.

But rotation causes frequencies with different m to be split.

Solar rotation

- **Analogy from atomic physics** that the energy levels of the hydrogen atom for different m are degenerate in the absence of a magnetic field. But a **magnetic field** lifts this degeneracy and **splits the levels.**
- In exactly the same way, the **rotation of the Sun** lifts the degeneracy of eigenfrequencies with different m.
- The amount of **splitting of a mode depends** basically **on the angular velocity** in the region where the mode has the largest amplitude.
- By studying the splittings of different modes having the largest amplitudes in different regions of the Sun, one can then obtain a **map of how the angular velocity varies in the interior of the Sun.**
- Figure shows a map giving the distribution of angular velocity in the interior of the Sun.
- **The Sun has a convection zone from $0.7R_\odot$ to $R_\odot$, within which the variations of angular velocity are confined, with a radial gradient of angular velocity at the bottom of the convection zone.**

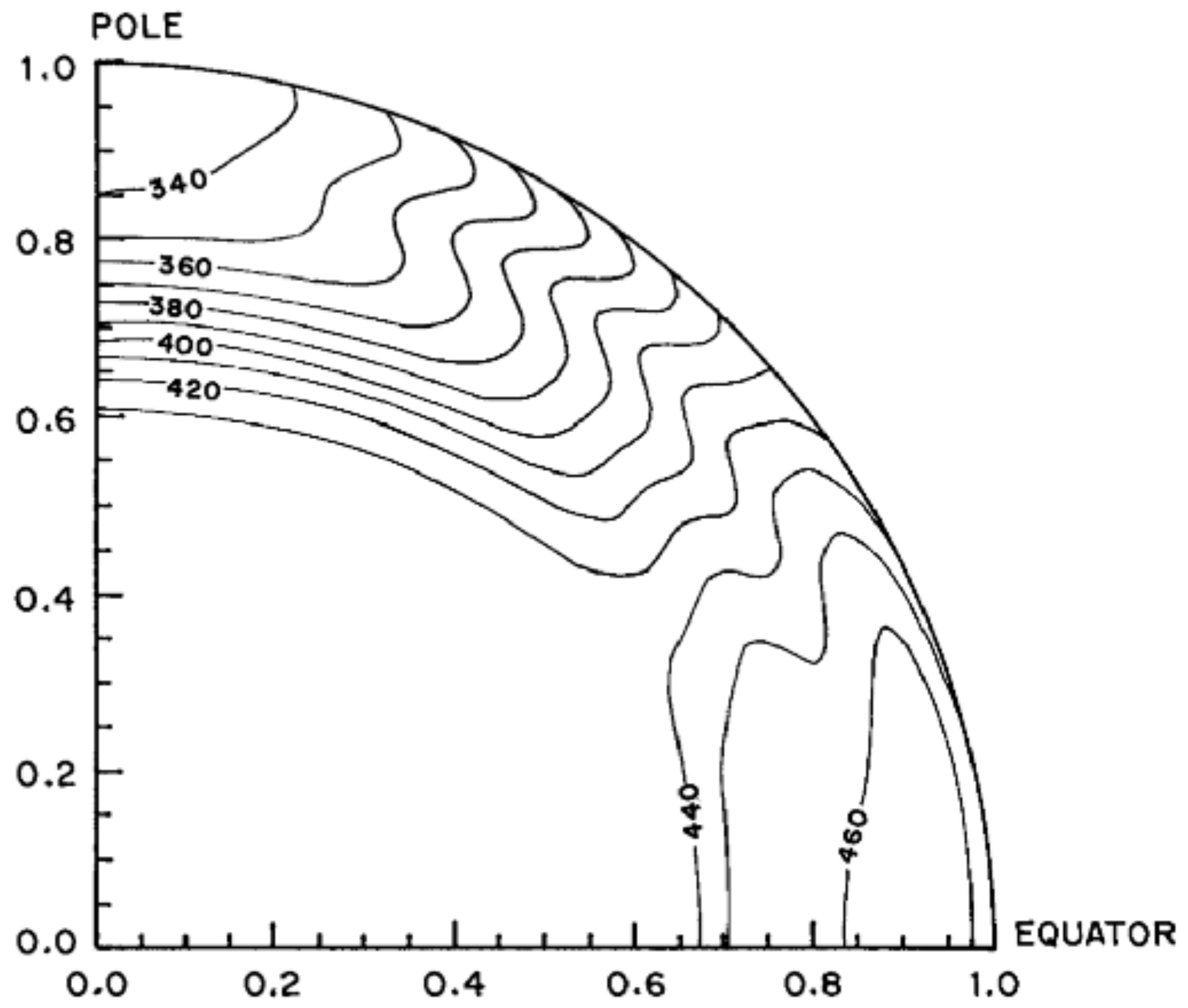
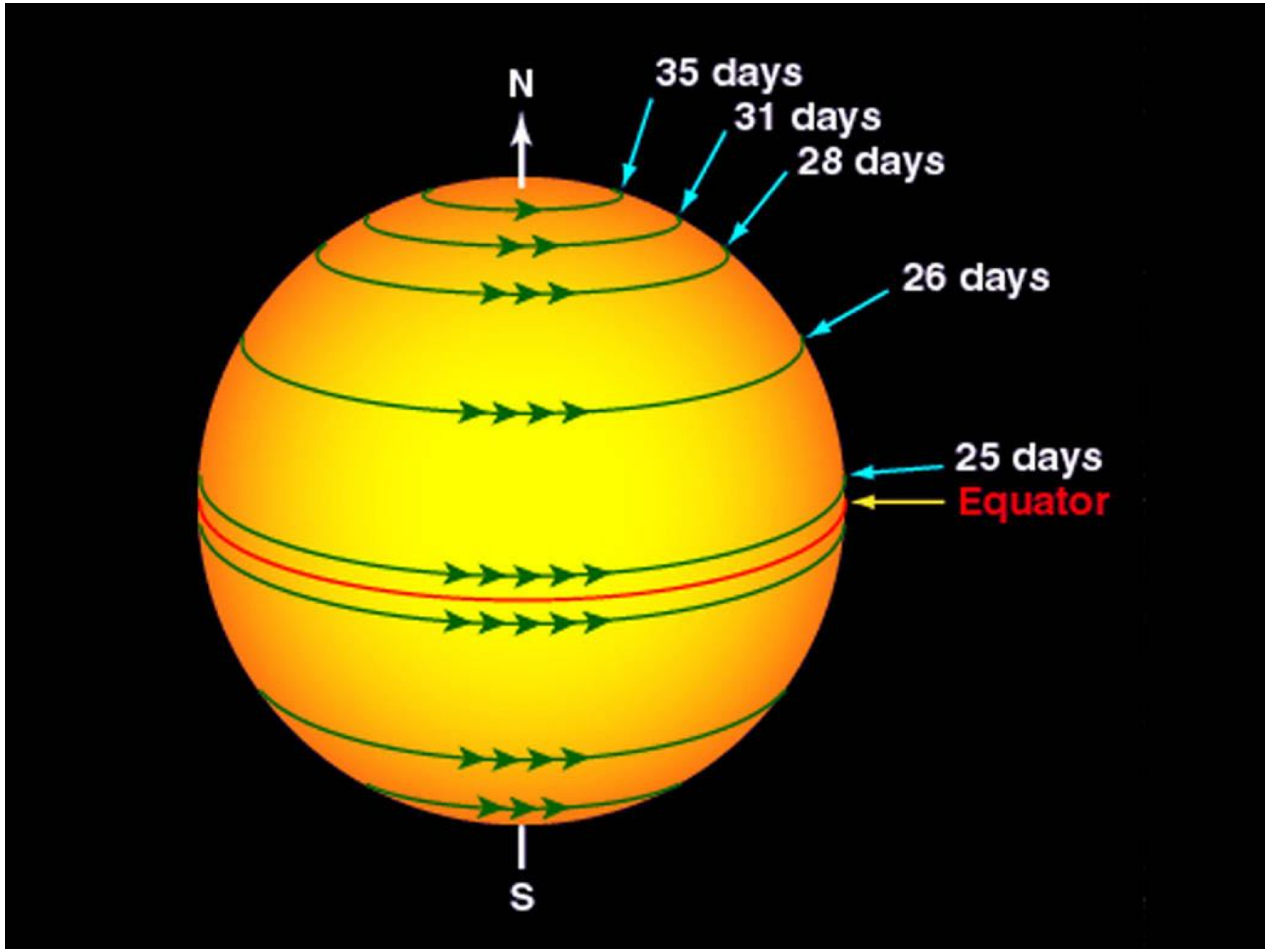


Fig. 4.15 The contours of constant angular velocity inside the Sun, as obtained by helioseismology. The contours are marked with rotation frequency in nHz. It may be noted that frequencies of 340 nHz and 450 nHz correspond respectively to rotation periods of 34.0 days and 25.7 days. Courtesy: J. Christensen-Dalsgaard and M. J. Thomson.

Solar differential rotation

The Sun rotates on its axis once in about 27 days. This rotation was first detected by observing the motion of sunspots. The Sun's rotation axis is tilted by about 7.25 degrees from the axis of the Earth's orbit.

The Sun's equatorial regions rotate faster (taking only about 24 days) than the polar regions (which rotate once in more than 30 days). This is called **"differential rotation"**



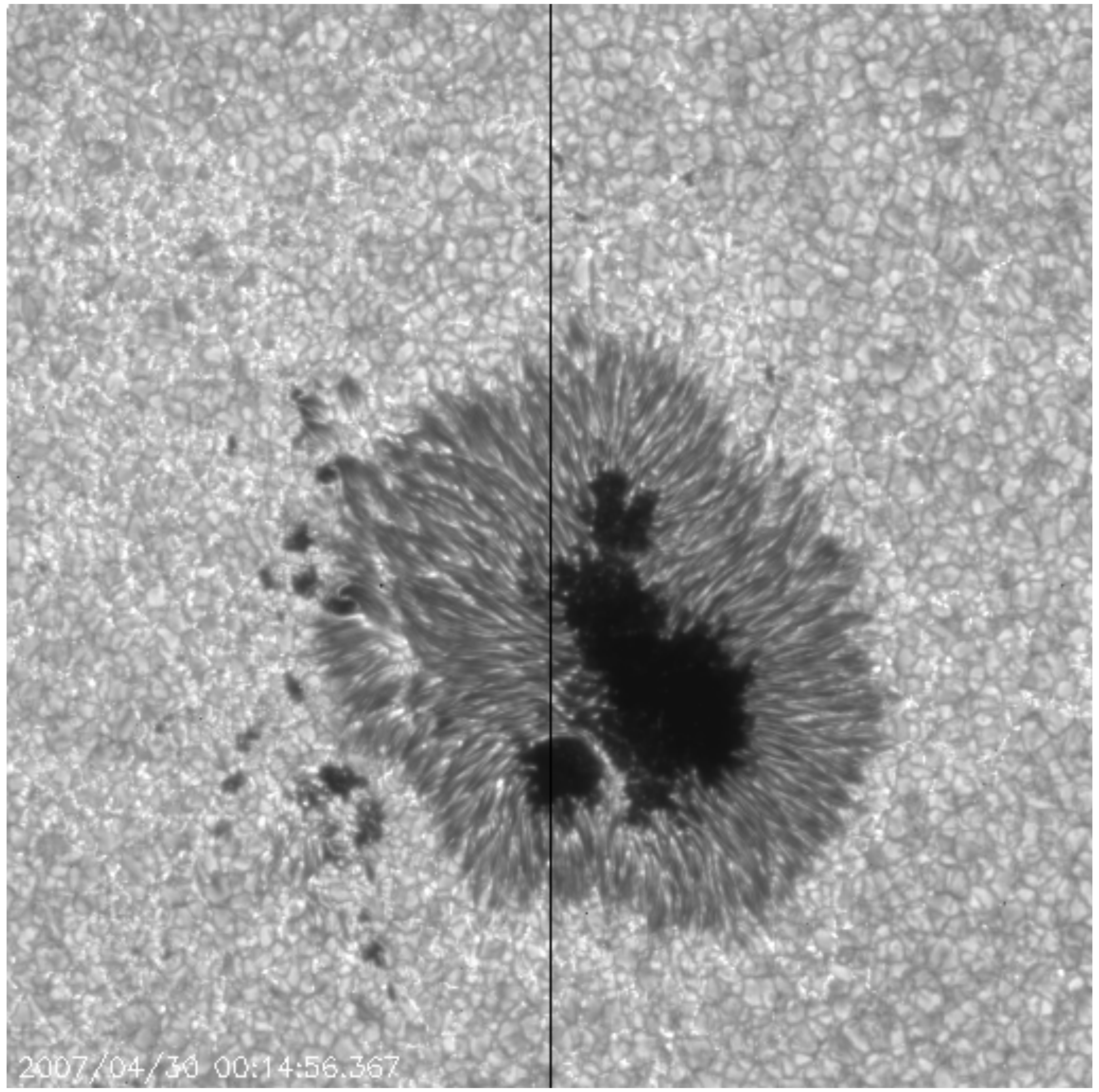
https://www.nasa.gov/mission_pages/sunearth/science/solar-rotation.html

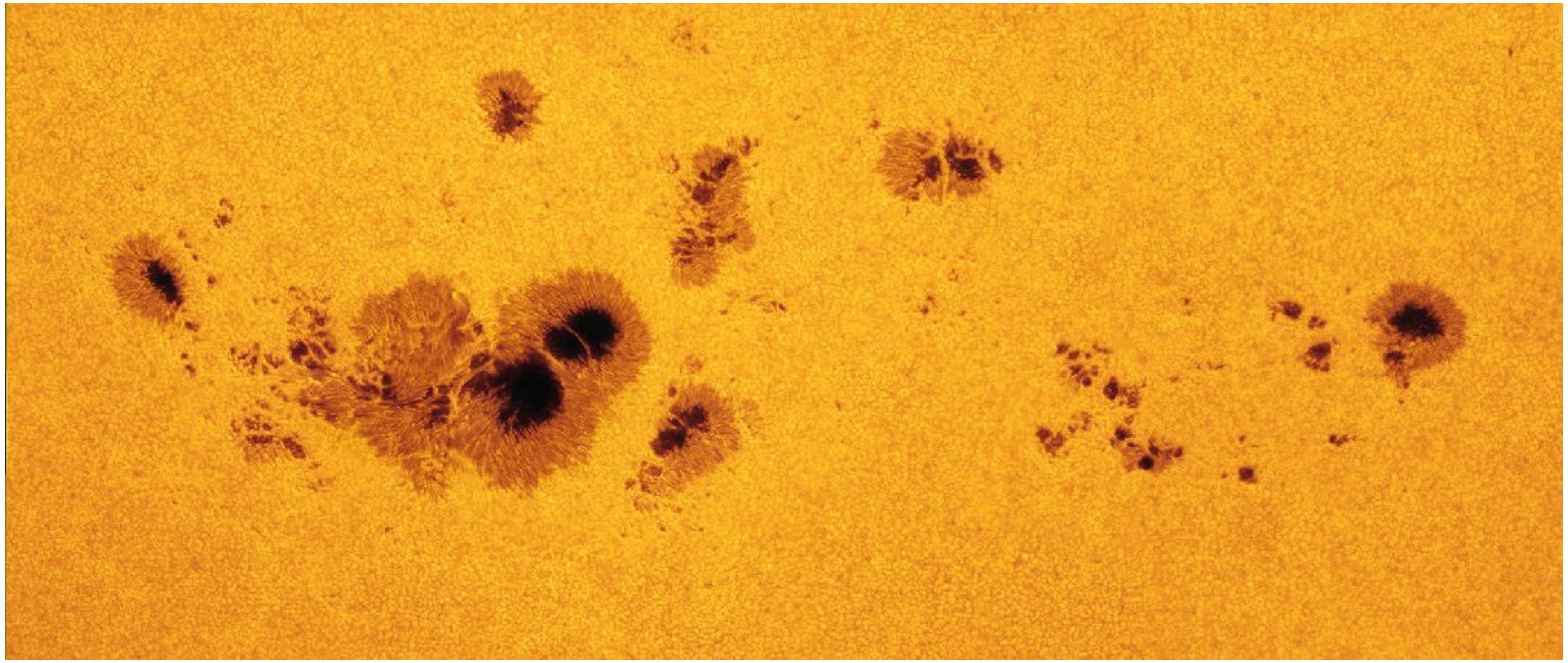
Solar magnetic field

- **What are the phenomena that tells us about the magnetic field in the Sun?**

Solar magnetic field

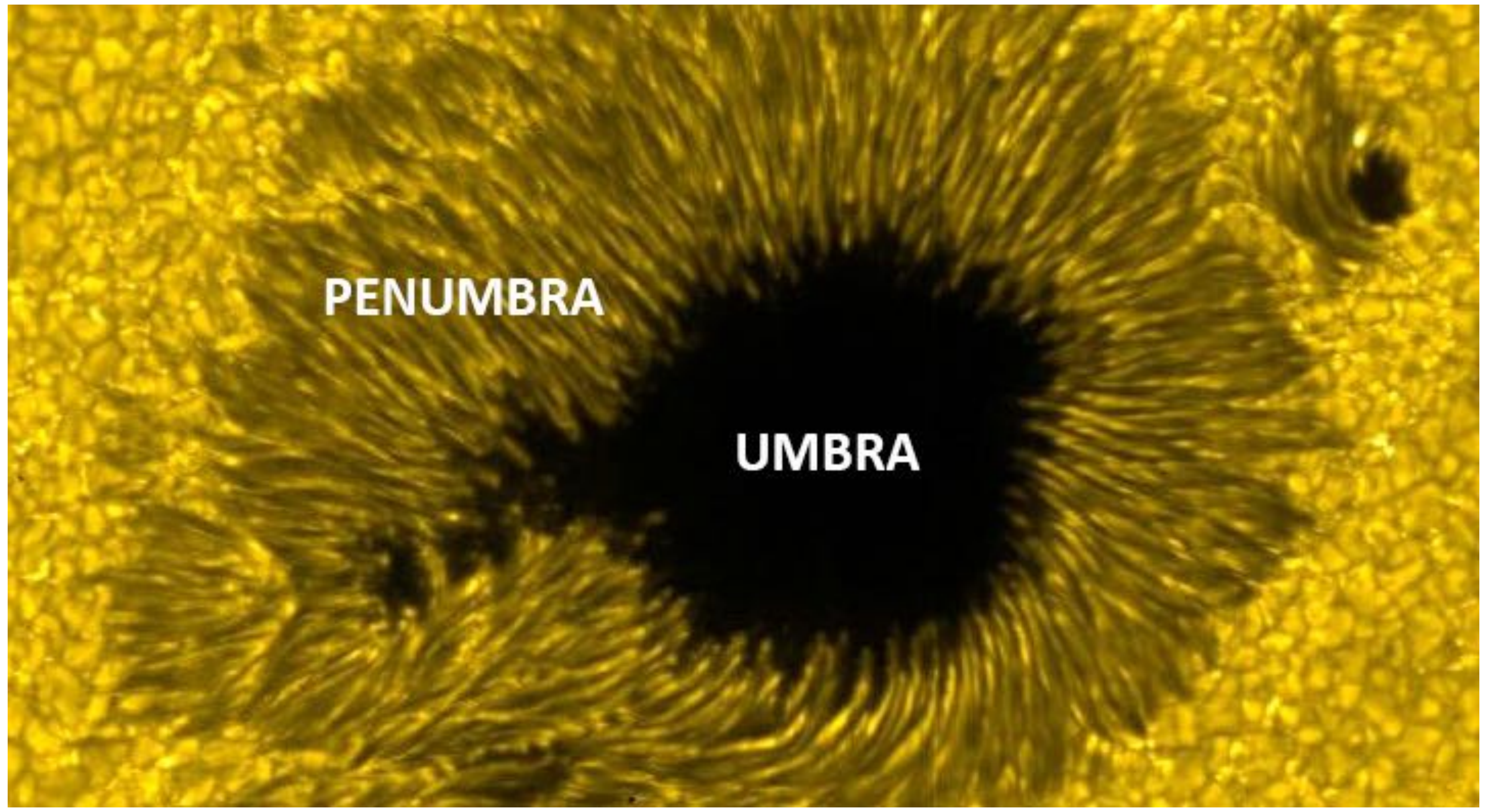
- **Sunspots**
- Hale (1908) discovered **Zeeman splitting in the spectra** of sunspots, thereby concluding that sunspots are regions of concentrated magnetic field of order **0.3 T**





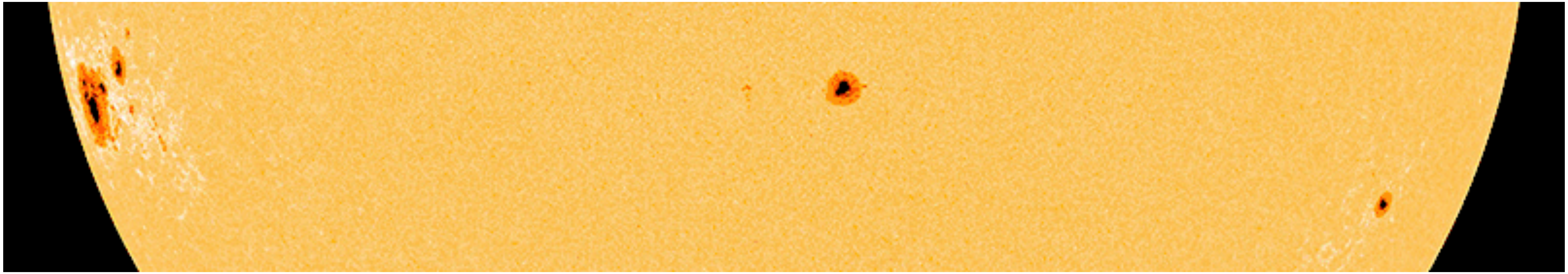
Solar magnetic field

- Sunspots **form on the surface of the Sun due to strong magnetic field lines coming up from within the Sun trough the solar surface** and appear visibly as dark spots compared to their surroundings.
- These sunspots which can become **many times bigger than the Earth** are always dark because they are much **cooler than the surrounding surface of the Sun itself.**
- A big sunspot can have a **temperature of 3700°C**.
- the temperature of the photosphere of the Sun which is about 5500°C
- A sunspot consists of two parts:
  - The dark part (umbra)
  - Lighter part around the dark part (penumbra)



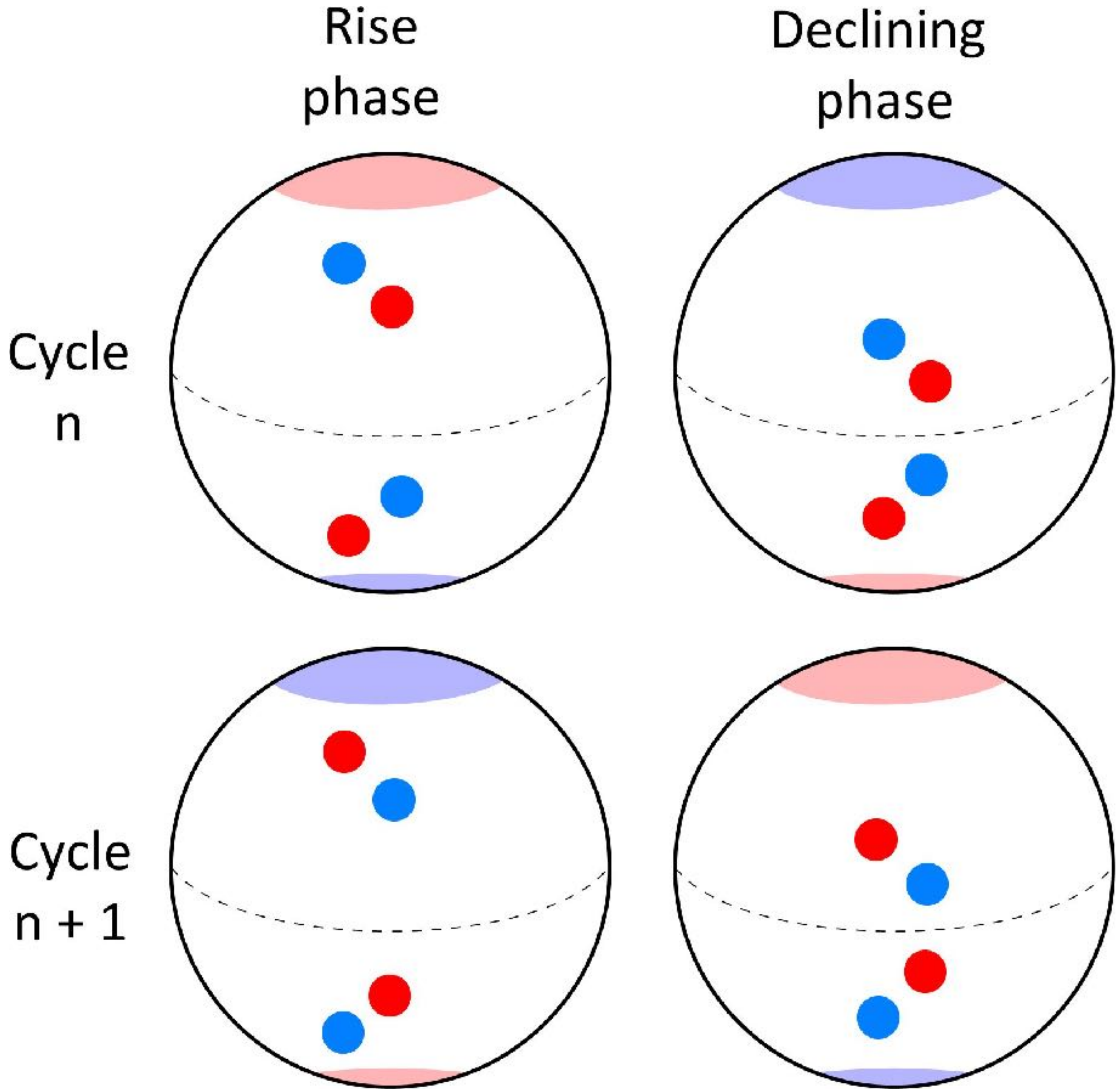
Solar magnetic field

- Sunspots are often found in groups, called **active regions**
- Often there are two large sunspots lying side by side at nearly the same solar latitude.
- two **sunspots in such a pair have opposite polarities,** making up a magnetic bipole.
- They also found that these **magnetic bipoles are oriented in opposite directions in the two hemispheres.**



Solar magnetic field

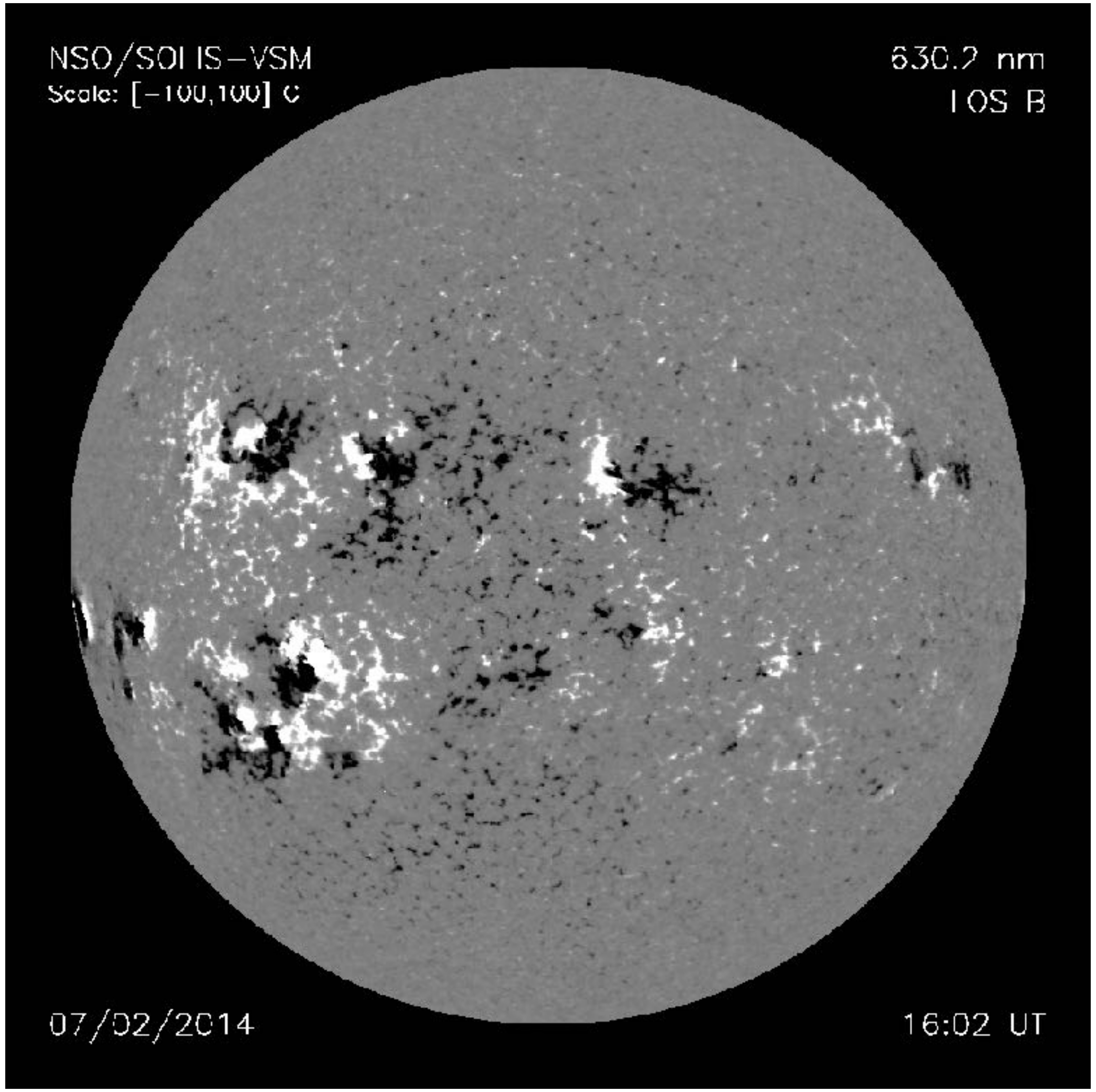
Sunspot orientations. Red/blue show inward/outward magnetic field. Sunspots occur in pairs, with the leading spot at lower latitude.
In each hemisphere, the polarity of the leading spot is the same as the dominant polarity at the start of the solar cycle.



https://twitter.com/mathewjowens/status/1019542311833931777/photo/1

Solar magnetic field

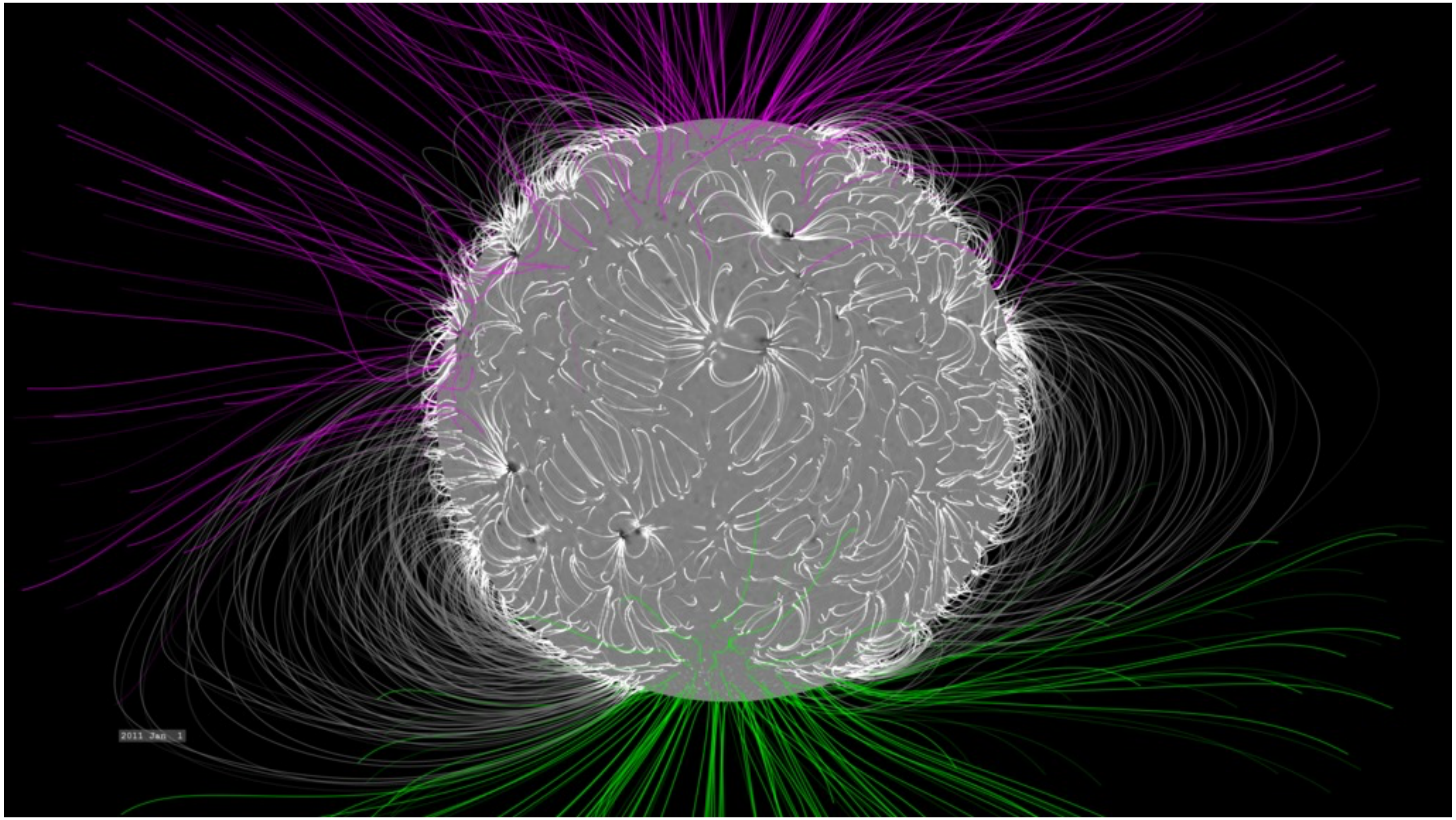
- **A** **magnetogram** **is an image taken by an instrument (magnetograph) that shows the strength, polarity, and location of the magnetic fields on the Sun.**
- Figure is a magnetogram image of the whole solar disk, where regions of positive polarity are indicated by white and regions of negative polarity by black, the regions without appreciable magnetic field being represented in grey.
- One notes that most bipolar magnetic regions are roughly aligned parallel to the solar equator.
- In the magnetic bipolar regions in the northern hemisphere, one finds the positive polarity (white) to appear on the left side of the negative polarity (black).
- This is reversed in the southern hemisphere, where white appears to the right of black.



https://nso.edu/data/nisp-data/magnetograms/

Solar magnetic field

- Magnetic field model of the Sun



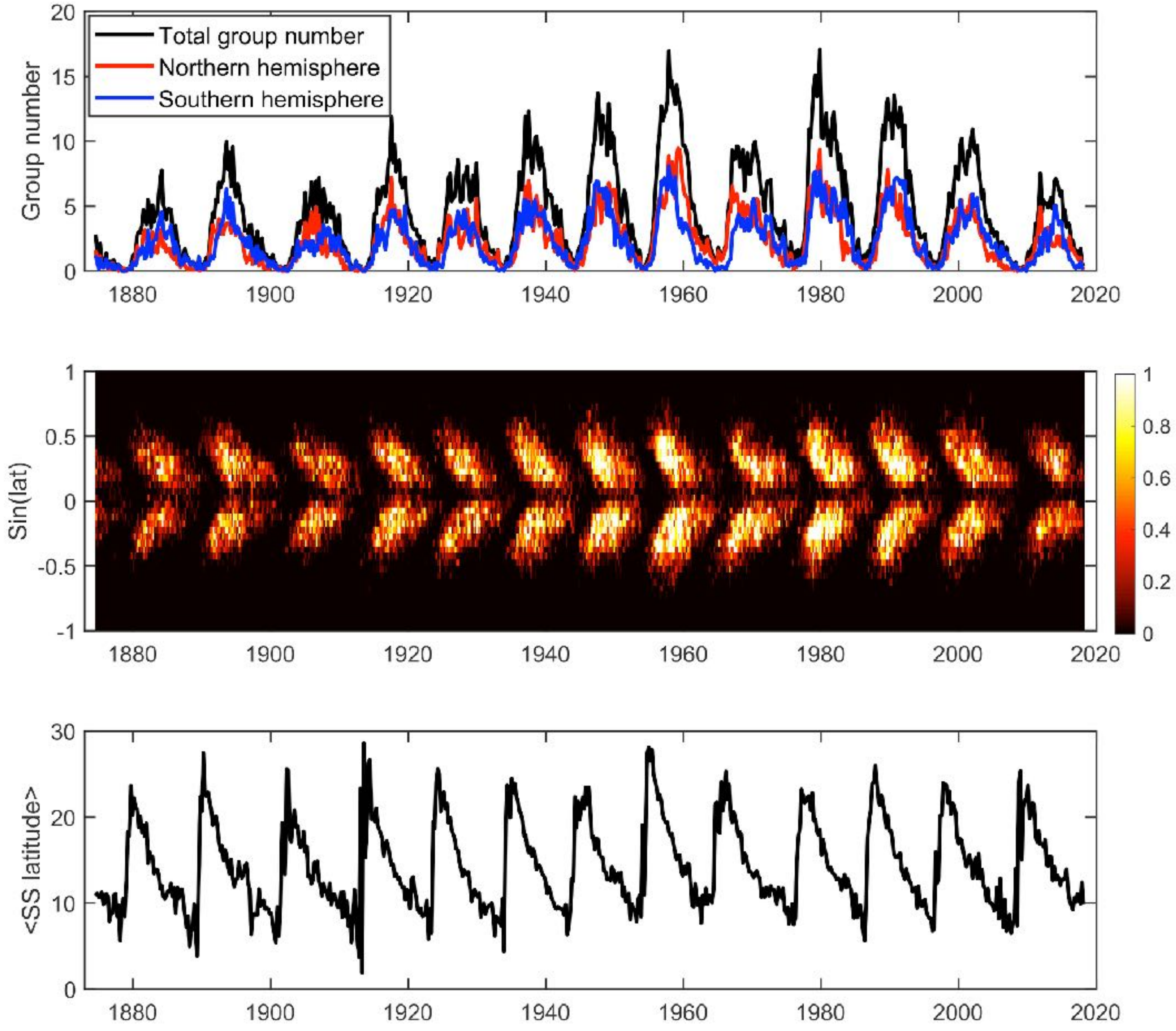
https://svs.gsfc.nasa.gov/4623

Solar cycle

- **What is the solar cycle?**

Solar cycle

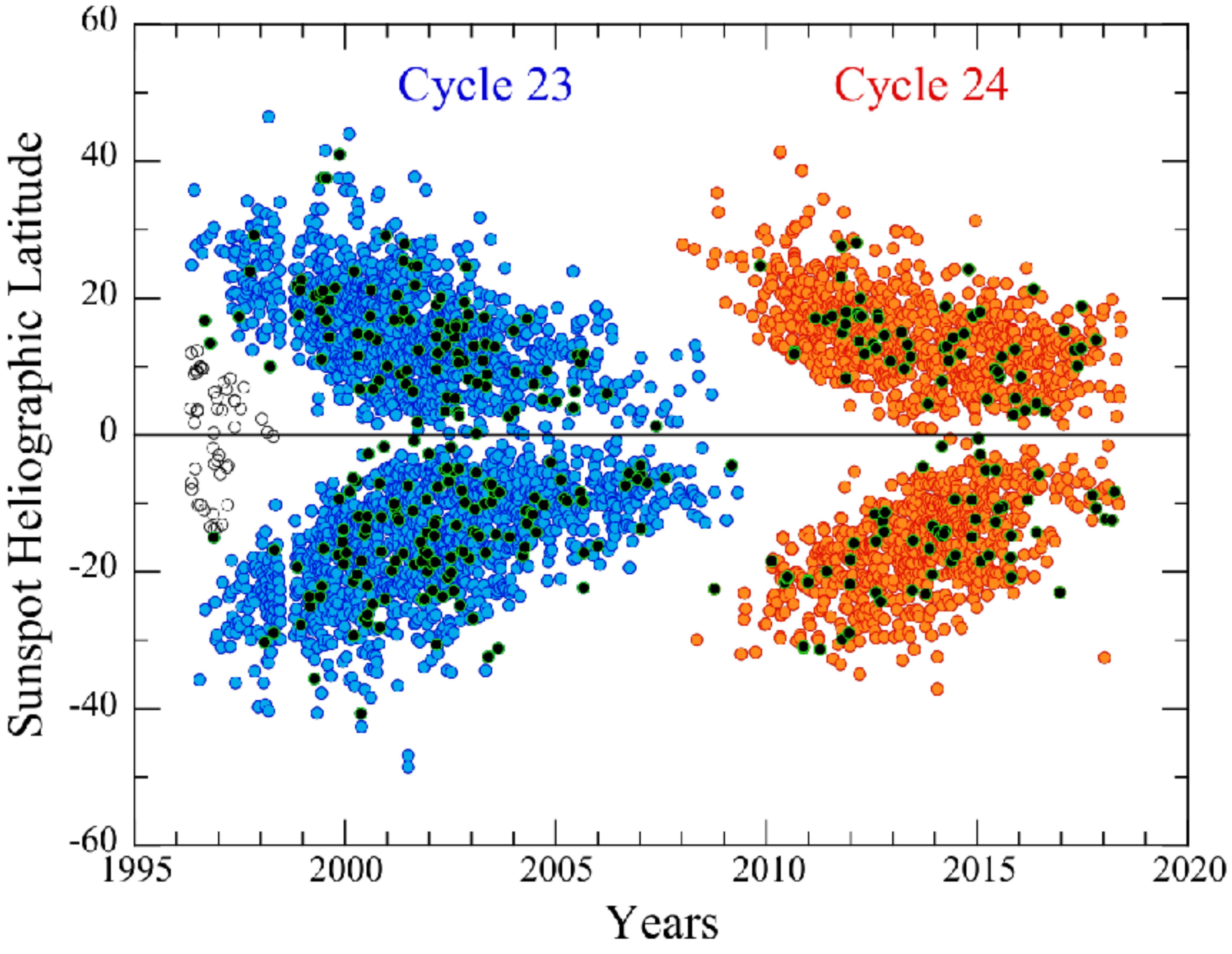
- **The number of sunspots on the solar surface increases and decreases in a cyclic fashion, with a period of about 11 years.**
- There is a phase in the cycle when not many sunspots are seen.
- Then sunspots start appearing at around 40 deg latitude.
- As time goes on, newer sunspots tend to appear at lower and lower latitudes. This is clearly seen in the so-called ***butterfly diagram***, which shows **covered surface with sunspots as a function of time and lattitude.**



https://twitter.com/mathewjowens/status/1019541490006220800/photo/1

Solar cycle

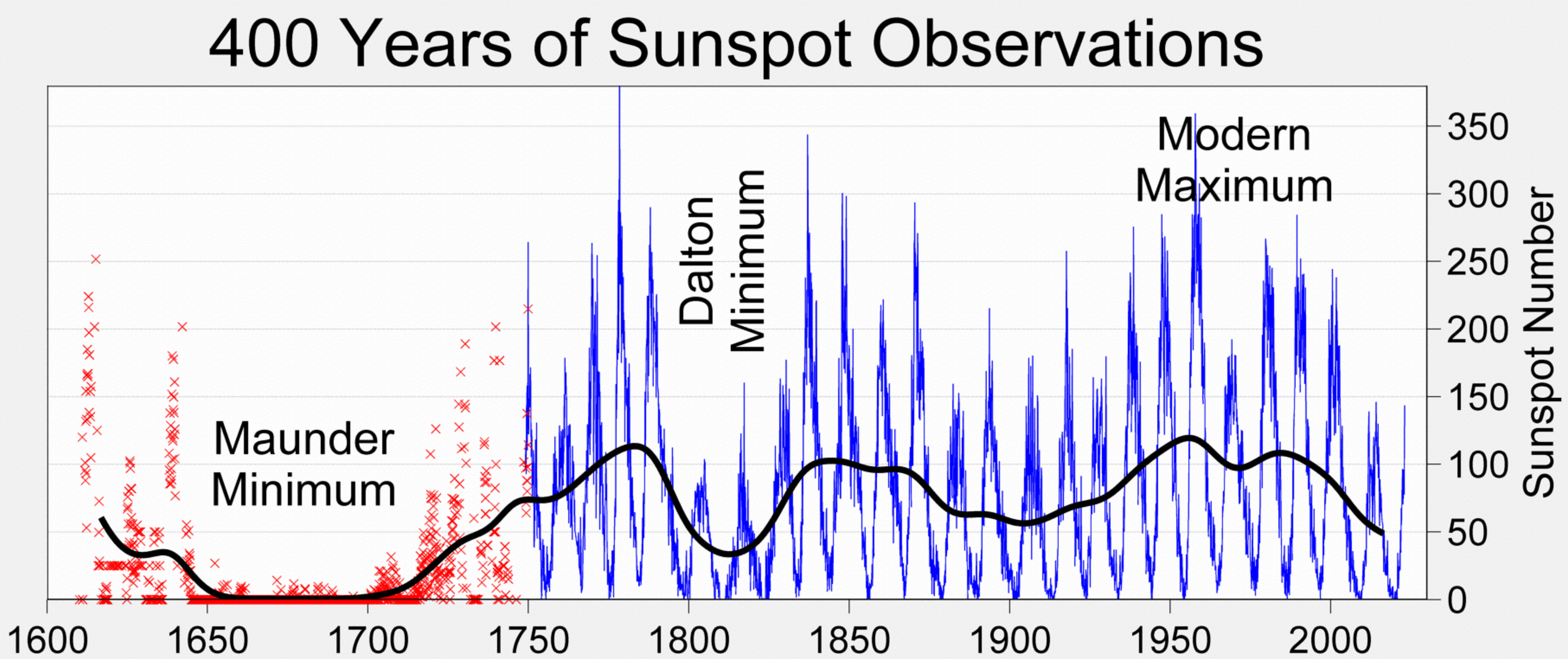
- On the butterfly diagram the horizontal axis is time. At any particular time, those ranges of latitude (vertical axis) are marked where sunspots appear. The butterfly pattern results from the equatorward shift of the latitude zones where sunspots are seen.
- Eventually only very few sunspots are near the equator.
- Then the next cycle begins with sunspots appearing again around 40 deg latitude.
- **It is found that the polarities of bipolar sunspots get reversed from one 11-year cycle to the next.**
- It thus implies that the **period of the solar cycle is actually 22 years,** if we want the magnetic field to come back to the initial configuration.
- **Many other stars have large starspots and also magnetic cycles like the Sun.**



http://hmi.stanford.edu/hminuggets/?p=2707

Solar cycle

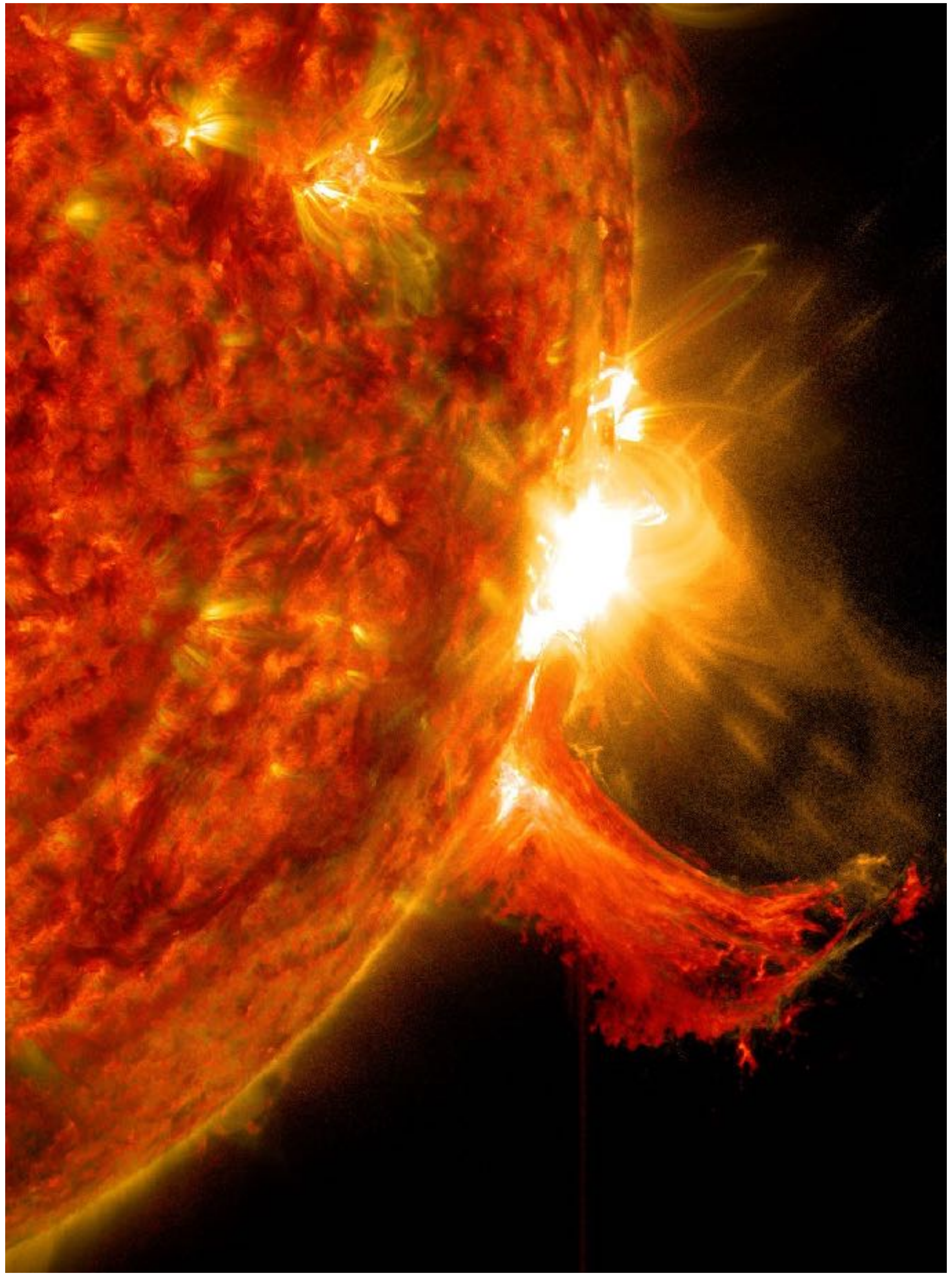
- The last 60 years has been high activity, now declining, with Dalton (DM) and Maunder (MM) minima in the 17th and 19th centuries.



https://en.wikipedia.org/wiki/Maunder_Minimum

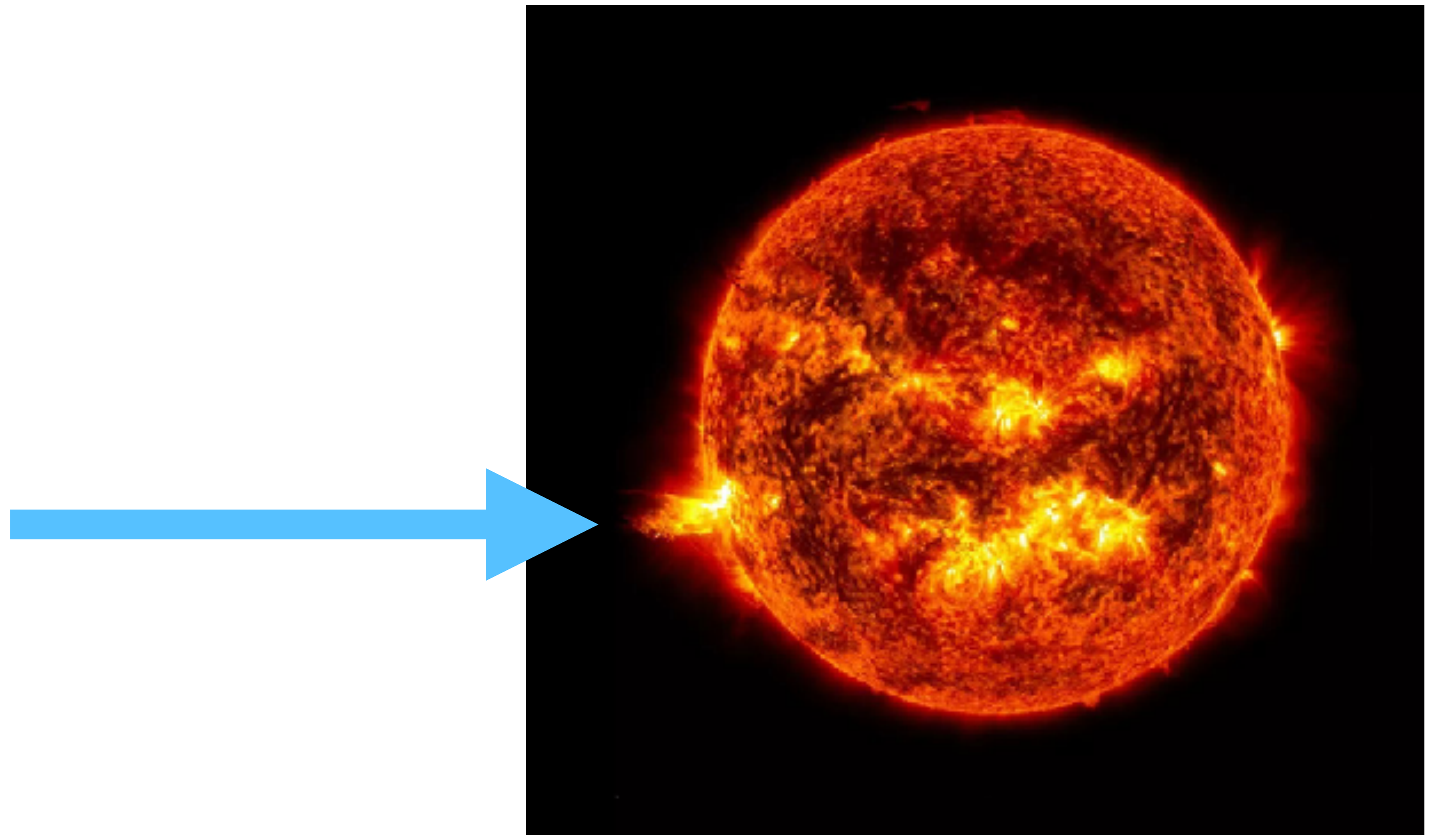
Solar flares

- **A solar flare is an intense localized eruption of electromagnetic radiation in the Sun's atmosphere.**
- Flares occur **in active regions** and are often, but not always, accompanied by coronal mass ejections, solar particle events, and other solar phenomena.
- The occurrence of solar flares varies with the 11-year solar cycle.
- Solar flares are thought to occur **when stored magnetic energy in the Sun's atmosphere accelerates charged particles in the surrounding plasma.** This results in the emission of electromagnetic radiation across the electromagnetic spectrum.



https://en.wikipedia.org/wiki/Solar_flare

Solar flares



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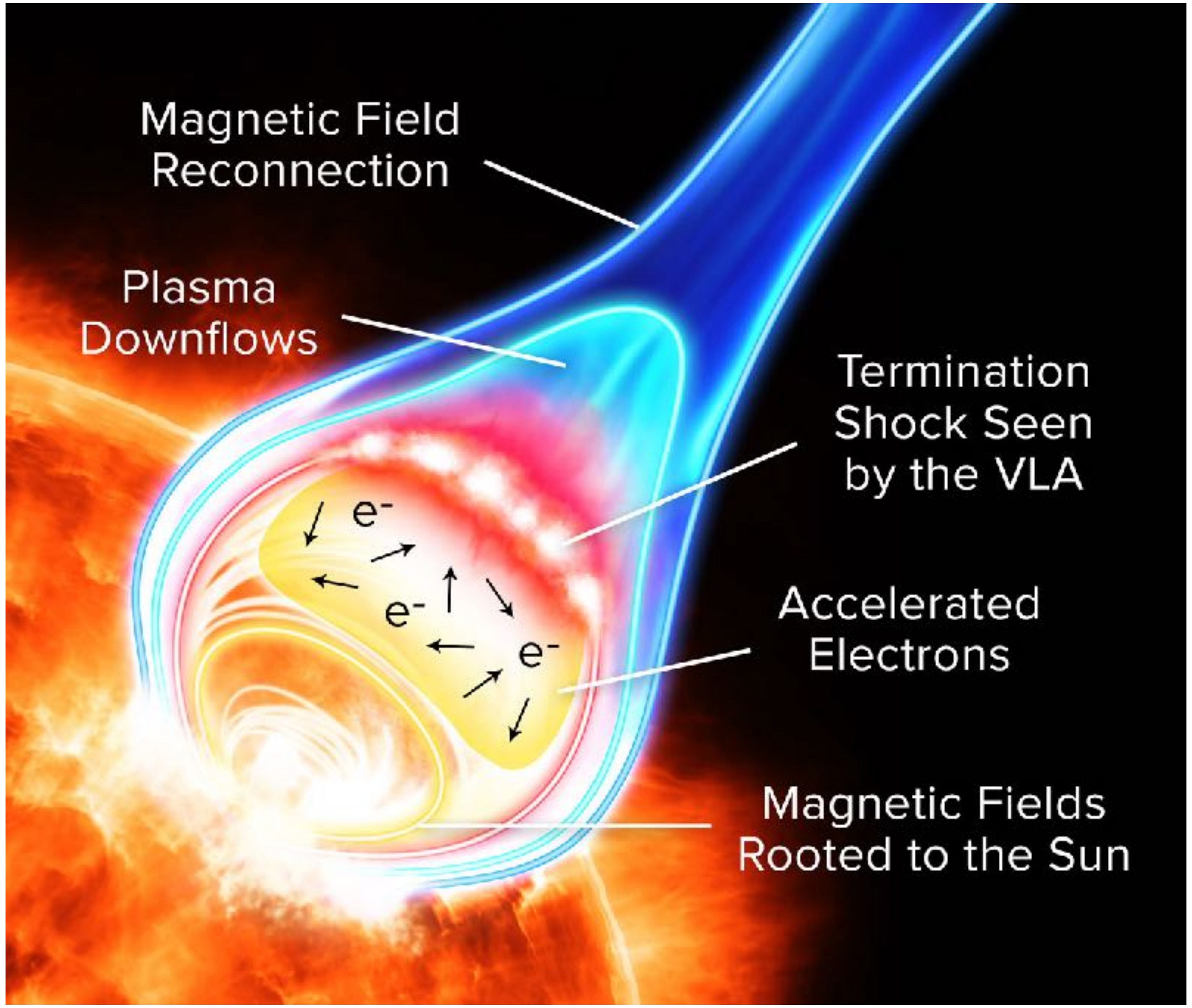
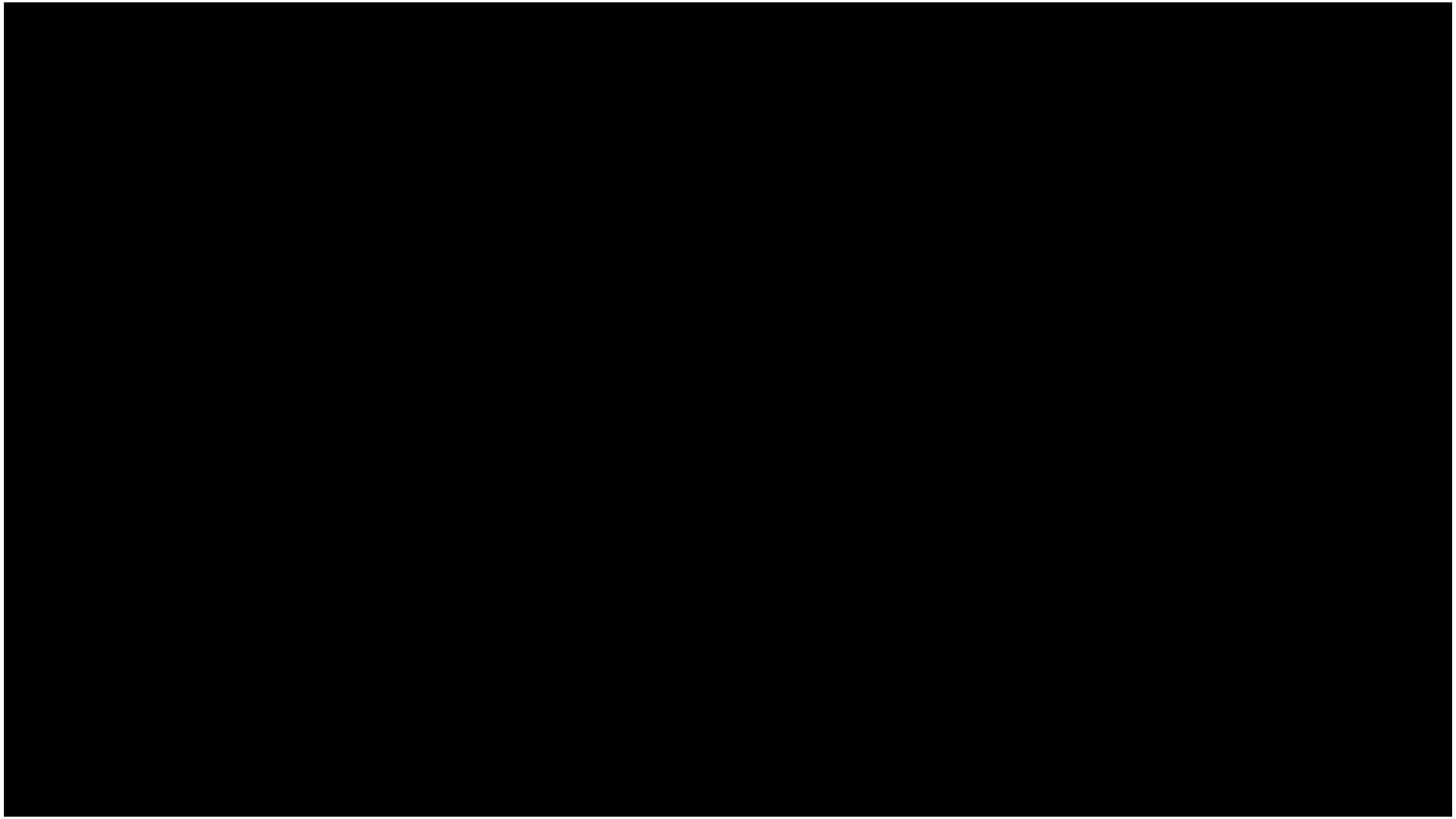


https://en.wikipedia.org/wiki/Solar_flare

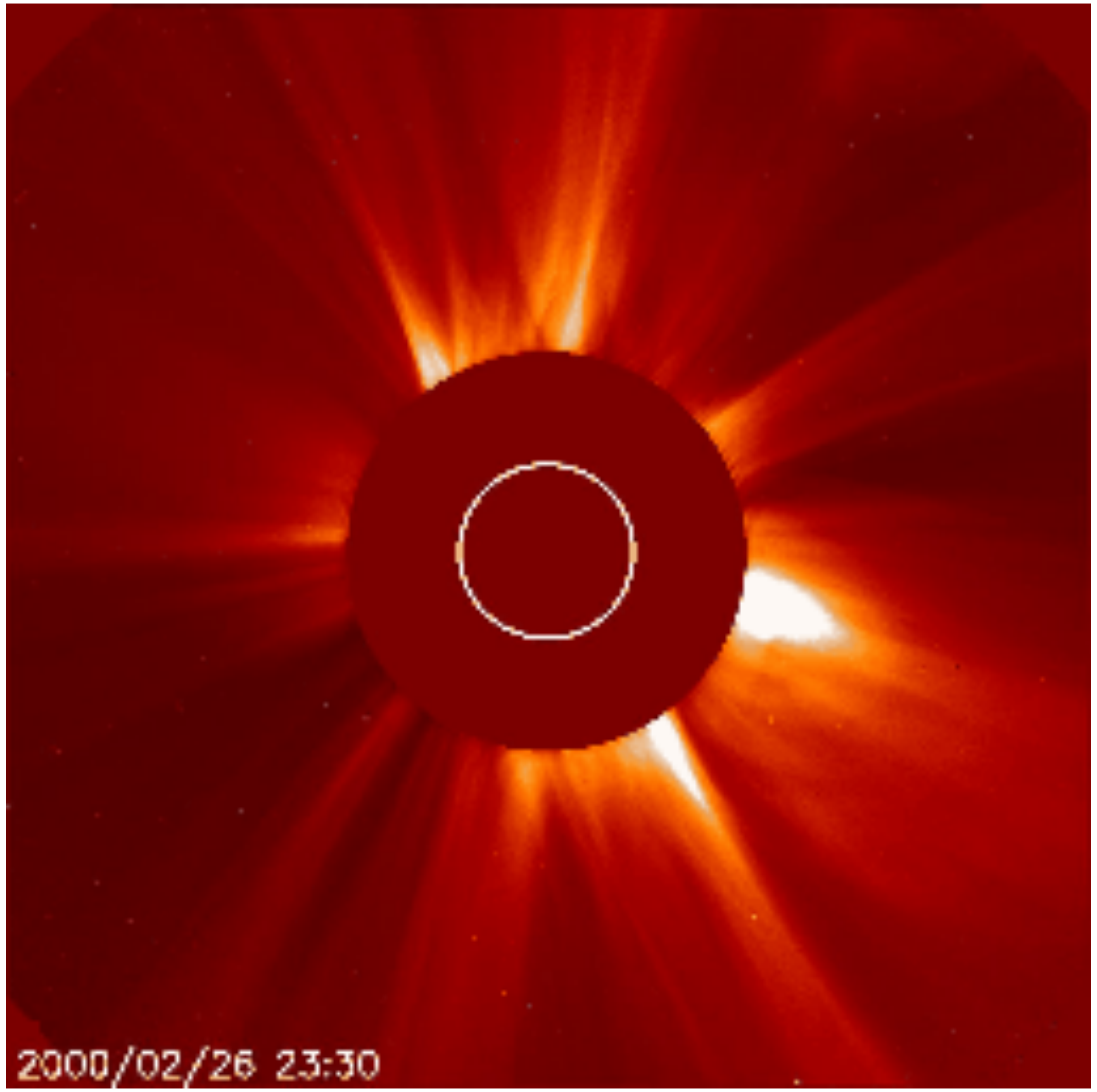
Solar flares



https://www.youtube.com/watch?v=HFT7ATLQQx8&ab_channel=NASAGoddard

Coronal Mass Ejection - CME

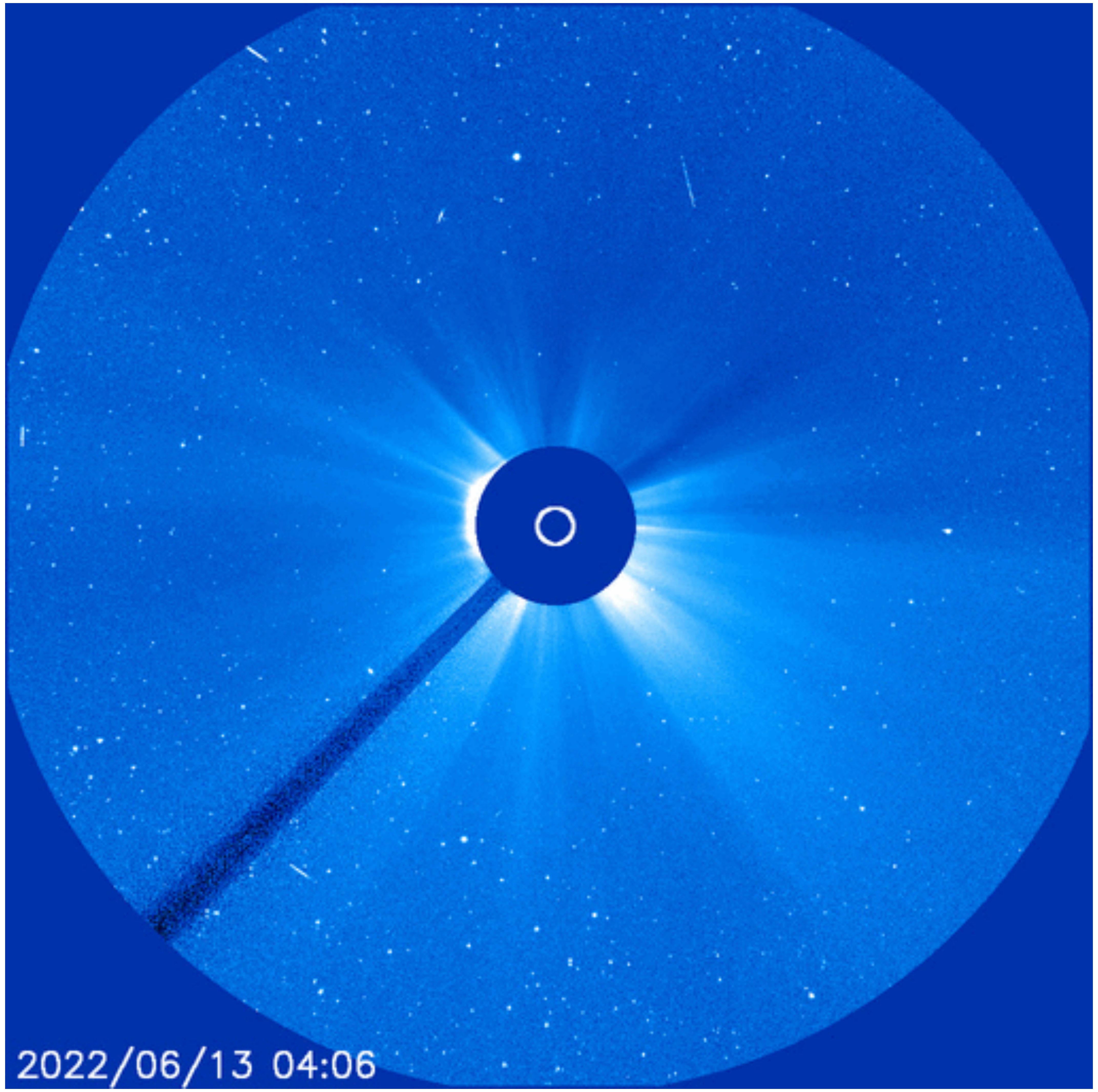
- **A coronal mass ejection (CME) is a significant release of plasma and accompanying magnetic field from the Sun's corona into the heliosphere.**
- CMEs are often associated with solar flares and other forms of solar activity, but a broadly accepted theoretical understanding of these relationships has not been established.
- If a CME enters interplanetary space, it is referred to as an interplanetary coronal mass ejection (ICME).
- ICMEs are capable of reaching and colliding with Earth's magnetosphere, where they **can cause geomagnetic storms, aurorae, and in rare cases damage to electrical power grids**.



https://en.wikipedia.org/wiki/Coronal_mass_ejection

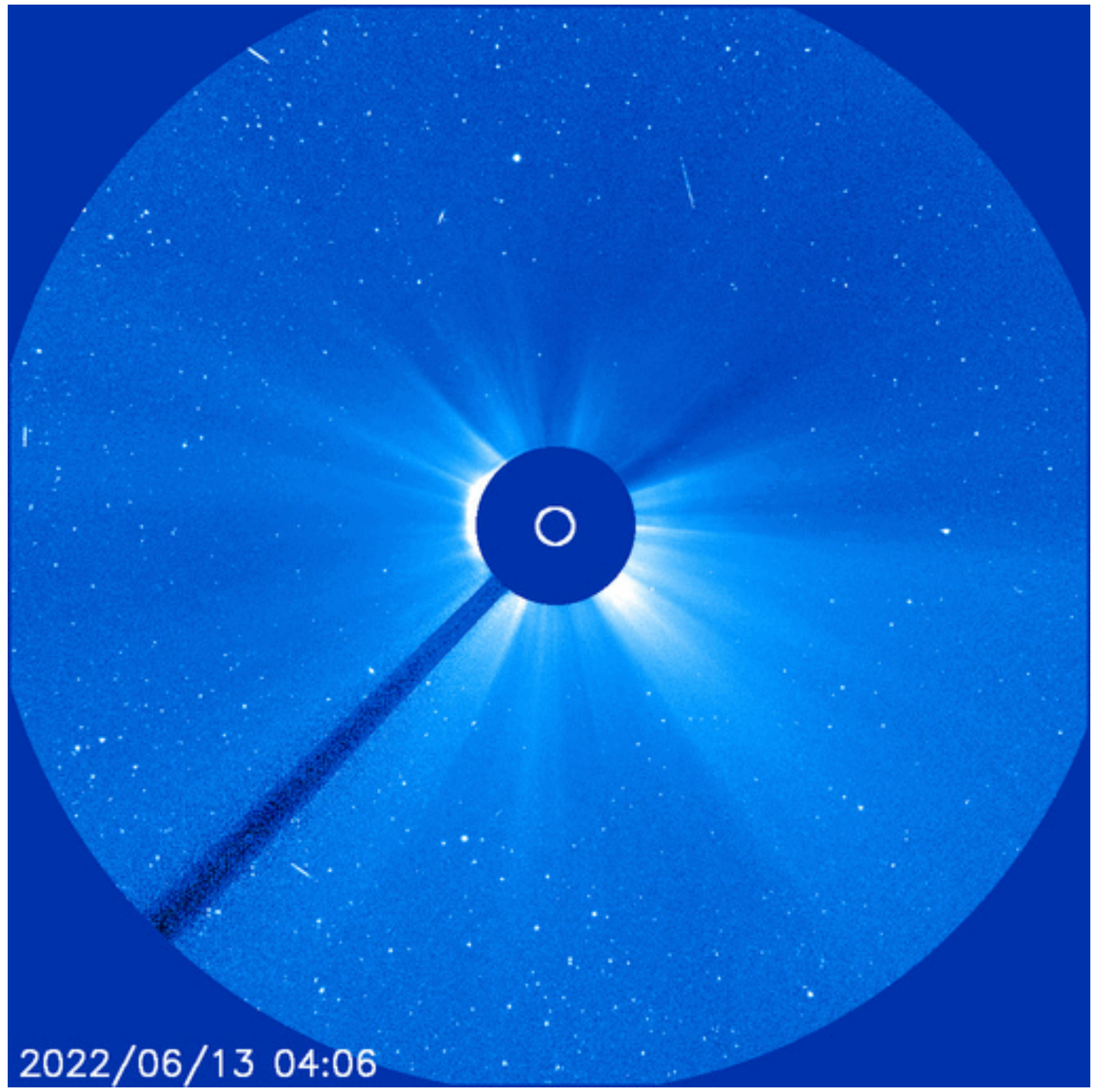
Coronal Mass Ejection - CME

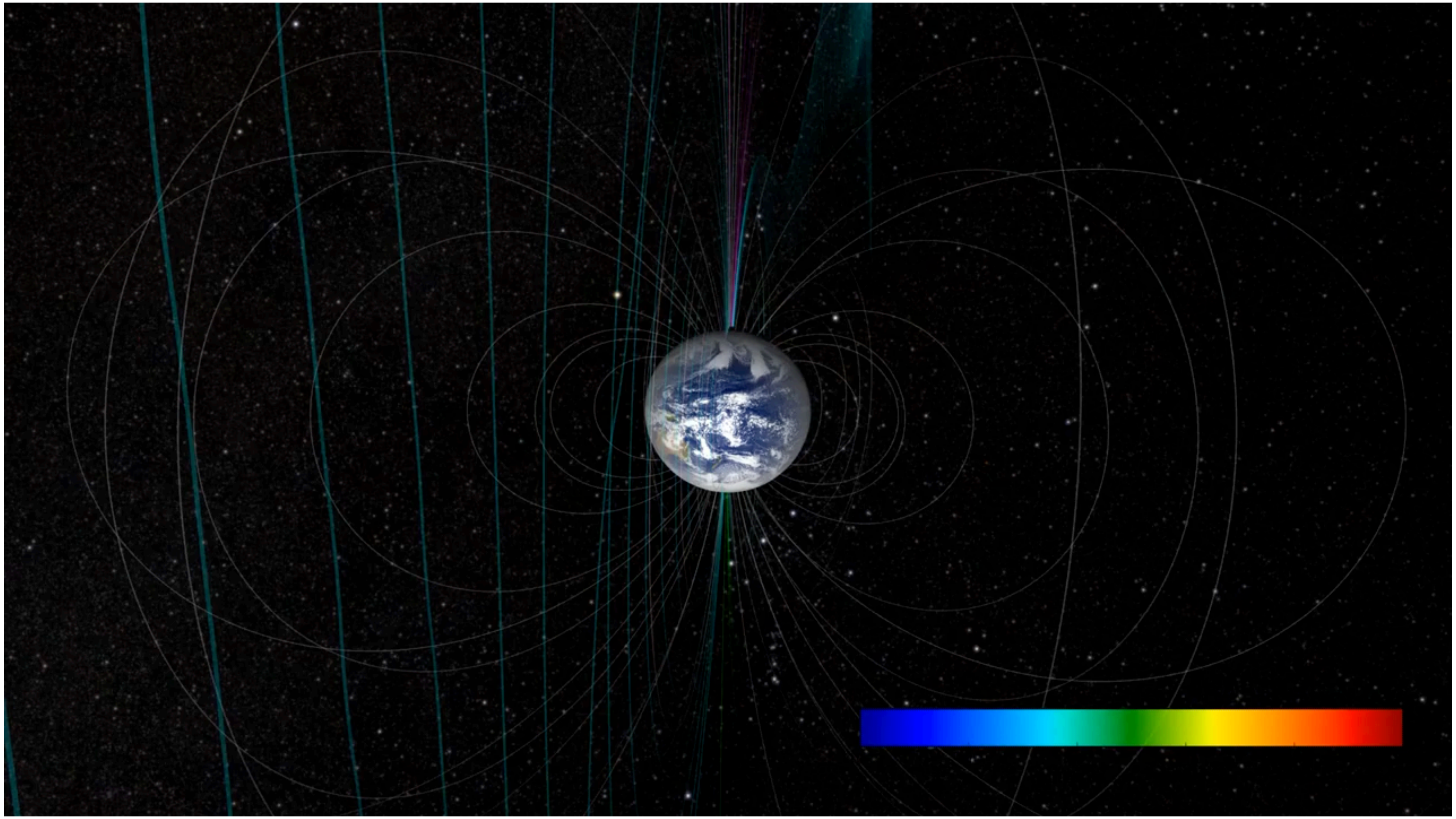
- The **largest recorded geomagnetic perturbation,** resulting presumably from a CME, was the **solar storm of 1859**. Also known as the **Carrington Event,** it disabled parts of the at the time newly created United States telegraph network, starting fires and shocking some telegraph operators.
- Near solar maxima, the Sun produces about three CMEs every day, whereas near solar minima, there is about one CME every five days.
- These types of **Solar activity are causing space wether**
- It is important to monitor space weather since it can disturb our power grids, radio network, satellites or harm astronauts



https://en.wikipedia.org/wiki/Coronal_mass_ejection

Coronal Mass Ejection - CME



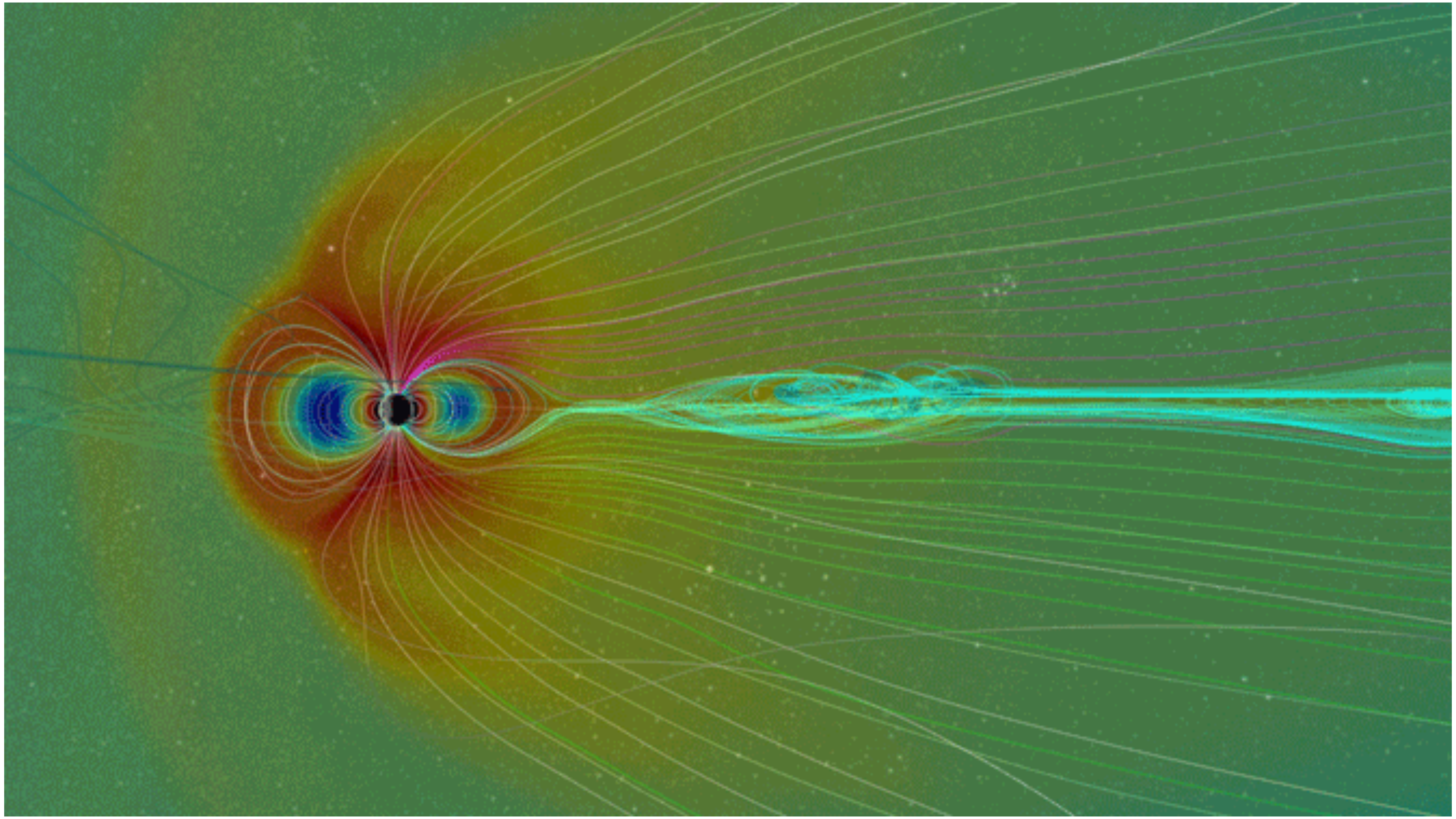


Earth's magnetosphere during a CME

https://www.youtube.com/watch?v=DyuTyEw3etk

Coronal Mass Ejection - CME

- Simulation of a very intense CME interacting with Earth's magnetosphere
- This CME could have caused the **Carrington Event**



https://svs.gsfc.nasa.gov/11660

Coronal Mass Ejection - CME

- Various websites that have up to date information on space weather

https://www.spaceweatherlive.com/en.html