ChatGPT

Stellar Simulation Data and Equations

Solar Structure & Internal Dynamics

Layered Structure (Core to Corona): The Sun's interior and atmosphere can be divided into concentric layers, each with characteristic size, temperature, density, and pressure. Below is a summary of these layers with approximate radial extents and physical conditions [1] [2]:

- **Core:** Extends from the center to ~25% of the solar radius (R_⊙). This is the nuclear burning region producing all the Sun's energy. **Temperature** ≈ 1.5×10⁷ K, **density** ≈ 150–160 g/cm³, and **pressure** on the order of 2×10¹⁶ Pa [3] [1]. The core holds ~34% of the Sun's mass within the inner 0.25 R_⊙, where the proton-proton fusion chain operates.

- **Radiative Zone:** From ~0.25 R_⊙ to 0.70 R_⊙. Energy is carried outward by **radiative diffusion** (high-energy photons scattering through dense plasma). **Temperature** falls from ~8×10⁶ K near the core edge to ~1.5×10⁶ K at 0.70 R_⊙ [4] [5]. **Density** drops steeply from ~20 g/cm³ at 0.25 R_⊙ to ~0.2 g/cm³ at 0.70 R_⊙ [6] [7]. Throughout this zone the material is stable against convection, so energy flow is purely radiative. The *mean free path* of photons increases with radius; it takes on the order of 10⁵–10⁶ years for core gamma-ray photons to random-walk out of the radiative zone [4].

- **Tachocline:** A thin shear layer around ~0.70 R_⊙ marking the transition between the solid-like rotation of the radiative interior and the differential rotation of the convective envelope [8]. Strong rotational shear here is thought to play a key role in the solar dynamo (see below).

- **Convective Zone:** From ~0.71 R_⊙ to 1.0 R_⊙ (surface). In this outer 30% by radius (but ~2% by mass), **convection** is the dominant energy transport. Plasma becomes cooler and more opaque (especially as heavier elements retain electrons) so radiation cannot carry all the flux, leading to convective instability [9] [10]. **Temperature** drops from ~2×10⁶ K at the base to ~5.8×10³ K at the visible surface [9] [11]. **Density** falls from ~0.2 g/cm³ at 0.71 R_⊙ to ~10^{−7} g/cm³ at the photosphere [12] [13]. Convective cells form, carrying hot plasma upward and cooler plasma downward. This turbulent overturning generates the **granulation** observed at the surface.

- **Photosphere:** The visible "surface" layer of the Sun, only a few hundred km thick (optical depth ~1 layer). **Temperature** ~5,780 K (with a temperature minimum ~4,400 K in the upper photosphere) [14] [15]. **Density** ~4×10^{−7} g/cm³ [13] and pressure ~0.1% of Earth's atmosphere. This thin layer emits the blackbody-like continuum that defines the solar effective temperature. It contains **granulation pattern** from underlying convection: cell diameters ~1,000–

2,000 km and lifetimes ~5–10 minutes (see below). Sunspots also reside here (see magnetic field section).

- **Chromosphere:** A ~2,000 km thick layer above the photosphere. **Temperature** rises from ~6,000 K at the photosphere back up to ~50,000 K at the top of the chromosphere [16]. **Density** ~10^{−7} to 10^{−8} g/cm³ (at 5×10⁴ K) [16]. The chromosphere is observed in Hα and Ca II lines; it appears as a reddish rim during eclipses. It contains dynamic **spicules** (see Transient Phenomena) and is the site of prominences looming against the sky. The upper chromosphere transitions rapidly into the corona in the **transition region** (a zone only a few tens of km thick where T jumps from ~50,000 K to >1×10⁶ K) [17].

- **Corona:** The outer atmosphere, extending **several solar radii** into space. **Temperature** ~1–2×10⁶ K in quiet corona, up to ~3×10<6> K in active regions, with hot flare plasma reaching tens of MK. **Density** is extremely low: ~10^{−14} g/cm³ (≈10⁸ cm^{−3} particle number density) in quiet Sun corona [18] [19]. Because the coronal plasma is optically thin, its radiation escapes freely. The corona is structured by magnetic fields into loops, arcades, and open field regions (coronal holes). It constantly expands into the solar wind. **Note:** despite million-K temperature, the corona's total emissivity is low (see Radiation section) due to the low density.

Standard Solar Model Profiles: A full Standard Solar Model provides continuous profiles T(r), ρ(r), P(r). For coding, one may use interpolated tables or analytic fits for these profiles. For example, the **center to surface** gradients approximately follow: temperature $T(r) \approx 15.0\,(1 - 0.73 (r/R_⊙)^{2})$ million K (rough fit inside core), density dropping roughly exponentially with scale height ~0.1 R_⊙ in the radiative zone, etc [12] [9]. For verification, the model should reproduce known boundary values (e.g. $T_{\text{core}}\approx1.5\times10^{7}$ K, $T_{\text{surf}}\approx5.78\times10^{3}$ K; $\rho_{\text{core}}\approx150$ g/cm³, $\rho_{\text{surf}}\sim10^{-7}$ g/cm³ [3] [13]). **Table 1** below summarizes key radii and conditions:

Region	Radius (R_⊙)	Temperature (K)	Density (g/cm³)	Notes
Core center	0	1.5×10⁷ [3]	150 [3]	Peak energy generation, $P\sim2\times10^{16}$ Pa
Core edge	~0.25 R_⊙	~8×10⁶ [20]	~20 [20]	99% of energy generated within inner 25% R
Radiative/ Conv. base	0.71 R_⊙	~1.5×10⁶ [4]	~0.2 [7]	Tachocline at ~0.69–0.71 R_⊙
Photosphere (surf)	1.0 R_⊙	5.8×10³ [21]	4×10^{−7} [22]	$T_{\text{eff}}=5778$ K; $P\sim0.1$% of sea-level atm

Region	Radius (R_⊙)	Temperature (K)	Density (g/cm³)	Notes
Chromosphere top	~1.001 R_⊙	~50,000 [17]	8×10^{−8} [16]	Transition region above this (T jumps to 10⁶ K)
Corona (base)	~1.005 R_⊙	~1–2×10⁶ [18]	~1×10^{−14} [18]	Quiet Sun corona; active regions hotter (~3 MK)

Granulation & Supergranulation: The solar **granulation** pattern is the direct manifestation of convection in the photosphere. **Granules** are cells of hot plasma ~1–2 Mm across (1000–2000 km) with bright centers (upwelling hot gas) and dark edges (cooling plasma descending). Typical granule properties: **horizontal cell size** ~1000 km, **lifetimes** ~5–10 minutes, **upflow speeds** ~1–4 km/s (order of sound speed) [23] [24]. Granules continually form and dissipate, contributing to a **granulation intensity contrast** of a few percent. For visualization, granulation can be modeled as a dynamic **Voronoi cell pattern** or turbulent noise field with a dominant scale of ~1 Mm; empirically, about 2×10^6 granules cover the Sun at any time [25]. A simple mathematical model is to generate cells with a characteristic size λ ~ 1000 km and lifetime τ ~ 8 min, possibly using random flow fields or cellular automata to evolve intensity. The number of granules scales roughly with surface area and inverse cell area (for other stars, adjust granule size via pressure scale height and gravity – see Stellar Variation section).

Supergranulation is a larger-scale convective pattern in the solar photosphere. **Supergranules** are ~20,000–30,000 km in diameter, much larger and longer-lived than granules [24]. They have **horizontal outflow speeds** of ~300–500 m/s (much slower than granules) and **lifetimes** on the order of 1–2 days [24]. Supergranulation is visible in Doppler maps as a cellular network. It is characterized by network magnetic fields accumulating at supergranular cell boundaries. In simulation, one could overlay a large-scale flow pattern with cell size ~30 Mm and velocity ~0.3 km/s to reproduce supergranular motions. It's essentially a turbulent convection scale arising from deeper layers. (There is also evidence for **mesogranulation** ~5–10 Mm scale, but it may be an artifact of averaging [26] – can be omitted for simplicity.)

Differential Rotation: The Sun's surface rotation rate varies with latitude. This *latitude-dependent angular velocity* can be fit by a simple polynomial. A commonly used empirical formula for the sidereal rotation (in degrees per day) as a function of heliographic latitude *φ* is [27] [28]:

$$\omega(\phi) = A + B\,\sin^2\phi + C\,\sin^4\phi,$$

with **coefficients**: - *A* ≈ 14.713 °/day, - *B* ≈ −2.396 °/day, - *C* ≈ −1.787 °/day [27].

At the equator (φ=0°), $\omega≈14.71$ °/day, corresponding to a rotation period ~24.47 days (sidereal). At mid-latitudes (φ=30°), the term $B\,\sin^2 30°$ slows the rotation to ~13.5 °/day; near the poles (φ→90°), ω drops to ~33.4-day period [29]. In radians per second, the equatorial angular velocity is $2\pi/({25.38~\text{days}})≈2.92\times10^{-6}$ s^{−1} (using the synodic period ~26.24 days to match Carrington frame [30] if needed). **Implementationally**, one can use the above equation to get the rotation rate at any latitude and then apply a surface differential rotation mapping. For internal rotation, helioseismology shows the radiative interior rotates uniformly (~≃432 nHz) while the convective zone has this latitudinal differential rotation roughly constant on cylinders. The **meridional circulation** (see below) also ties into the differential rotation through angular momentum transport.

Meridional Circulation: The Sun exhibits a slow flow pattern from equator to poles at the surface and back to the equator at the bottom of the convection zone – often likened to a **conveyor belt**. Observations show a poleward surface flow of **~10–15 m/s** (≈20–30 mph) at low to mid-latitudes [31]. This flow extends to the poles (no evidence of a flow reversal until very high latitude) and is thought to plunge inward near the poles, returning equatorward at the base of the convection zone [32]. The full circulation loop may take on the order of 17–22 years. For simulation, one can impose a **meridional flow velocity** $v_\theta(r,\theta)$ that is poleward in the surface layers and returns at depth; a simple stream function can ensure mass conservation. For example, at the surface, $v_\theta(\theta)\approx15\sin(2\theta)$ m/s directed toward the pole (peaking at mid-latitudes). This large-scale flow is crucial for magnetic flux transport (it advects magnetic fields, influencing the solar cycle period). **In practice**, to visualize it, one might not render it directly, but it affects the evolution of surface magnetism (which can be represented by drifting sunspot latitudes, etc.).

Magnetic Field & Dynamo Physics

Global Solar Dynamo (α–Ω Dynamo): The Sun's 11-year cycle is powered by a magnetic dynamo operating in the convection zone and tachocline. In mean-field modeling, the **induction equation** for the magnetic field **B** (in an electrically conducting plasma with velocity field **v**) is:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B} + \alpha \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B}),$$

where **v** includes large-scale flows (differential rotation Ω and meridional circulation) and turbulent motions, **α** represents the net effect of helical turbulence (the α-effect converting toroidal field to poloidal), and **η** is the magnetic diffusivity [33] [34]. In the **α–Ω dynamo paradigm**, the two primary ingredients are:

- The **Ω-effect**: Differential rotation stretches poloidal field lines into a toroidal orientation. Quantitatively, an initial poloidal field B_p will be wound up so that $\partial B_{\phi}/\partial t \approx (B_p \cdot \nabla Ω) r$ (order-of-magnitude form), generating a strong toroidal field in the tachocline. The Sun's shear (equator rotating faster than poles by ~30%) is sufficient to amplify field strengths up to ~10⁵ G in the overshoot layer at the base of convection zone (where sunspot flux tubes likely form).

- The **α-effect / Babcock–Leighton process**: Turbulent convection and helical flows (especially in the presence of rotation) induce an emf that converts toroidal field back to poloidal. In the Sun, this is thought to be accomplished by the emergence and decay of tilted bipolar sunspot regions (the **Babcock–Leighton mechanism**): when sunspot pairs (with east-west oriented polarities) emerge, the tilt (Joy's Law) causes a slight bias where following-polarity flux diffuses poleward and cancels/opposes the existing polar field, eventually reversing it [35] [36]. In mean-field models, one often uses a source term for poloidal field: $ \partial A/\partial t = \alpha B_{\phi}$ (with *A* the poloidal vector potential) in the upper convection zone. For example, a simple **dynamo cycle equation** pair can be written as:

$$\frac{dB_\phi}{dt} = \Omega \frac{dA}{dr} - \frac{B_\phi}{\tau_d}, \qquad \frac{dA}{dt} = \alpha B_\phi - \frac{A}{\tau_d},$$

where *A(r)* represents poloidal field and *B_φ* toroidal; τ_d is a diffusive decay timescale. This is a very simplified 0D caricature, but it produces oscillatory solutions. **In code**, one would not simulate MHD fully, but can implement the *effects* of the dynamo: e.g. a time-dependent sinusoidal or observed **Butterfly diagram** pattern for sunspot emergence latitudes and polar field strength. The key cycle parameters include a **period** of ~11 years for sunspot cycle (22 years for full magnetic polarity cycle), an equatorward drift of active latitudes from ~±30° toward the equator (Spörer's law), and polar field reversals near cycle maxima [37] [38].

Sunspot Magnetic Structure: Sunspots are regions of concentrated magnetic field that suppress convection. They consist of a dark **umbra** and a lighter **penumbra**. In the **umbra**, the field is very strong (~0.2–0.37 T) and mostly vertical. Measured **field strengths** at the umbra center are typically **1800–3700 G** (0.18–0.37 T) [39]. The umbral field is inclined only ~10–20° from vertical near the center [40] [39], leading to the dark appearance (strong field reduces convective heat flux and results in cooler temperatures ~4200 K). In the **penumbra**, the field fans out and is more inclined (~70° from vertical at outer edge). Field strength in penumbra is lower, around **700–1000 G** at the photospheric level [41] [42]. The penumbra's filamentary structure is due to channelled flows (Evershed flow) along nearly horizontal field lines. **Size:** Typical whole sunspot diameters range from ~3000 km (small pore) to >50,000 km for giant spots [43]. Umbrae might be ~a few thousand km across, penumbrae adding another few thousand km annulus. **Lifetimes:** large sunspots can persist for weeks, while small spots decay in days. **Implementing sunspots:** One could define an active region by a concentrated vertical field patch (e.g. a Gaussian profile of B), where B~3000 G at center dropping to ~1000 G at radius ~5,000 km. Visually, this reduces brightness (via cooler blackbody and limb darkening laws). The *Wilson depression* (sunken umbra) might be approximated by a slight concave deformation for realism.

Coronal Magnetic Loops: The corona is structured by magnetic loops which confine hot plasma. **Scaling laws** relate loop length (L), plasma temperature (T), and pressure (p). An empirical *Rosner-Tucker-Vaiana (RTV) scaling* for static coronal loops in thermal equilibrium is [44]:

$$T_{\max} \approx 1.4 \times 10^3 \left(pL\right)^{1/3},$$

with *T* in K, *p* in dyne cm^{−2}, *L* in cm [45]. This yields roughly: for a loop of length L=5×10⁹ cm (50,000 km) at pressure p=1 dyne cm^{−2} (corona base pressure ~0.1 Pa), $T_{\max}\sim$ 3.2 MK. Conversely, a loop observed at T≈1 MK and L=50,000 km would have base pressure ~0.01 dyne/cm². Another consequence is a scaling for **density**: $n_e \propto (T^2/L)$ (from hydrostatic equilibrium and energy balance) – more explicitly, at apex temperature T, $n_e \approx 10^8\,T^2_{\text{MK}}/L_{(10^9 \text{cm})}$ cm^{−3} (order-of-magnitude). These laws mean longer loops require higher pressure to reach the same T, and high-pressure loops get hotter. **Coronal loop implementations** can use these relations to set plasma emissivity: e.g. if a user "heats" a loop to 10 MK, the code can adjust density via $p\sim T^2/L$ to satisfy energy balance. **Loop arcades** in active regions follow the magnetic field topology; one can sample loop lengths from tens to hundreds of Mm and assign temperatures accordingly (1–3 MK in active region loops, higher for flare loops). The **scale height** for coronal plasma is $H \approx \frac{2k_B T}{\bar{m} g_{\odot}} \approx 50,000~\text{km}$ at 1 MK, which sets typical loop heights (many loops appear truncated by gravity).

Solar Cycle Magnetic Parameters: Over ~11-year cycles, the global field oscillates. Some key parameters for the solar cycle (as per Babcock-Leighton model and observations):

- **Polar Field Strength:** ~10 G at solar minimum (unipolar field at poles) flipping sign at maximum [35]. The polar field serves as seed for next cycle's toroidal field. A stronger polar field at minimum tends to yield a stronger subsequent cycle.

- **Sunspot Latitude Drift:** New cycle spots emerge at ~30°–35° latitude and then progressively at lower latitudes, approaching ~7° by cycle end (but never at the exact equator due to Hale's polarity law). This drift can be encoded as, e.g., $\lambda_{\text{spot}}(t) \approx 35° \cos^2(\frac{\pi t}{2T})$ for half-cycle *T*.

- **Joy's Law (Tilt):** Bipolar spot groups' tilt angle relative to east-west increases with latitude: approximately $\delta \approx 0.5 \lambda$ (e.g. ~5° tilt at 10° latitude, ~15° at 30° lat). This tilt is crucial for flux dispersal in BL mechanism. One could incorporate this by spawning paired spots with slight north-south asymmetry in polarity distribution.

- **Flux Transport:** Meridional flow (~10 m/s) carries surface flux poleward; turbulent diffusion (~200 km^2/s) spreads flux. These can be parameterized in a surface flux transport model if simulating magnetic maps. For visualization, it suffices to slowly move trailing polarity patches poleward over a cycle.

- **Cycle period and amplitude:** Not constant – in code, allow parameters for cycle length (e.g. 11 yrs ~ one "unit" in time slider) and max sunspot number or coverage. Typically ~0.1% of the Sun's surface is covered in spots at peak (sunspot area ~2000 micro-hemispheres). The code may use a sine function for overall cycle modulation of magnetic activity: e.g. $B_{\text{spot}}(t) = B_0 \sin(\pi t/T)$ for each hemisphere's spot flux.

- **Active region emergence rate:** at solar maximum, new sunspot groups appear ~2 per day; at minimum, essentially zero for months. For a simulation, one can increase the rate of sunspot appearance as a function of cycle phase.

These parameters together ensure the simulated Sun exhibits an activity cycle akin to reality [46]. *Example:* at cycle max, ~10–20 large sunspots might be visible with field ~3000 G umbrae, numerous bright plages and ~X-class flares; at minimum, only occasional small spots at ~5° latitude with low-level activity.

Radiation & Spectral Emission

Limb Darkening: The Sun's brightness decreases from disk center to limb due to temperature gradients in the photosphere. Limb darkening can be quantified by an empirical formula for specific intensity $I(\mu)$ (where $\mu=\cos\theta$ is the cosine of the viewing angle from center, with $\mu=1$ at disk center). A simple **linear law** is:

$$\frac{I(\mu)}{I(1)} = 1 - u\,(1 - \mu),$$

where u is the **limb darkening coefficient**. The coefficient depends on wavelength: shorter wavelengths have stronger limb darkening (larger u). For example, at **600 nm (visible yellow)**, $u \approx 0.56$, while at **320 nm (near UV)**, $u \approx 0.95$ [15]. This means in the blue/UV the limb is much darker relative to center (because we see higher, cooler layers), whereas in the red/IR the brightness is more uniform. For more accuracy, a multi-parameter fit is used. The Sun is well-fit by a 2nd-order polynomial at 550 nm [47]:

$$\frac{I(\mu)}{I(1)} = 0.3 + 0.93\,\mu - 0.23\,\mu^2 \quad (\text{at } 550\ \text{nm})\ 【40\dagger L217 - L225】.$$

This yields intensity at the limb (μ=0) about 30% of center intensity [48]. For coding, one can use pre-tabulated **limb darkening coefficients** (e.g. from Neckel & Labs). A convenient approach is to include a set of coefficients for a few wavelength bands or for bolometric intensity. For instance, a typical **broadband (photovisual)** limb darkening for the Sun is: $I(μ)/I(1) ≈ 1 - 0.47(1-μ) - 0.23(1-μ)^2$ [49]. The code can interpolate u as a function of wavelength (monotonic decrease of u from ~0.9 in UV to ~0.5 in red to ~0.1 in far IR). For other stars, u differs (cooler stars have stronger limb darkening in optical due to molecular opacity, etc.), so in presets these coefficients should be adjusted according to T_{eff} and $\log g$ (available from stellar atmosphere models).

Spectral Energy Distribution (Blackbody vs Actual Solar Spectrum): A star's spectrum deviates from a perfect blackbody due to absorption lines and wavelength-dependent opacity. The Sun's **effective temperature** ~5778 K would imply a blackbody peak around 500 nm. The **actual solar spectrum** (integrated over disk) is close to blackbody in continuum shape but with significant dips (Fraunhofer lines) and an overall suppression in UV relative to blackbody. For example, the Sun's observed UV flux at 300 nm is orders of magnitude lower than a 5800 K blackbody prediction, due to line blanketing by metals and the temperature minimum region [14] [15]. Conversely, the **infrared** flux is closer to blackbody because the outer layers become warmer again in the chromosphere for some lines (though CO molecular bands cause absorption dips around 4.6 μm). **Quantitatively**, one can provide a correction function $f(λ)$ such that $F_λ^{\text{sun}} = f(λ) B_λ(5778~K)$. For instance, $f(λ)$ might be ~0.1 at 200 nm (strongly depressed UV), rising to ~0.8–0.9 at 500 nm (visible, with modest line absorption), and ~1.0–1.1 in the near-IR (some slight excess due to limb brightening in CO lines) [50]. The code can use an approximate **solar spectral irradiance dataset** (e.g. ASTM G173 or NASA WHI reference spectrum) for realism. Key takeaway: **absorption lines** (e.g. Ca II H/K at 393 nm, Fraunhofer G band ~430 nm, etc.) should be imprinted if high spectral fidelity is needed. For broadband color rendering, treating the Sun as a 5778 K blackbody is adequate, but for scientific rigor instruct Claude to include e.g. a lookup table of solar spectral flux versus wavelength normalized to the blackbody continuum [51] [19].

Coronal Emissivity & EUV/X-ray Emission: In the corona, radiation is primarily from an **optically thin plasma** in collisional equilibrium. Emission comes from **free-free (bremsstrahlung)** continuum and millions of spectral lines of highly ionized atoms (Fe IX–XXIV, O V–VIII, etc.). The emissivity per volume is $ε = n_e^2 \, \Lambda(T)$, where n_e is electron density and $\Lambda(T)$ is the **radiative loss function** (erg cm³ s^{−1}). $\Lambda(T)$ is strongly temperature-dependent and has been calculated by various authors [52] [53]. **Characteristic behavior:** it peaks at certain temperatures where strong line cooling is present. For solar-composition plasma at coronal densities (~10^8–10^9 cm^{−3}), $\Lambda(T)$ has a broad maximum around *T* ~10^5–10^6 K (due to lines of ions like C IV, O VI at ~10^5 K and Fe X–XIV at ~10^6 K). For example, one set of calculations found a peak in the cooling curve near $2×10^5$ K with $\Lambda \approx 10^{-22.7}$ erg cm³/s, and another broad peak ~10^6 K with $\Lambda \sim 10^{-22}$ erg cm³/s [54]. Above ~3×10^6 K, as the plasma becomes fully ionized to Fe XXVI etc., line cooling drops and free-free (which scales ~$T^{1/2}$) dominates, so $\Lambda(T)$ decreases (to ~10^{−23.5} at 10⁷ K). **In implementation**, one can use a piecewise approximation or table for $\Lambda(T)$ for 10⁴ K to 10⁸ K. Then, given a coronal temperature, the code can compute emissivity $ε = n_e^2 \Lambda(T)$ for EUV/X-ray visualization. For example, at *T* =1 MK and $n_e=10^9$ cm^{−3}, $ε \sim 10^{-22} \times (10^9)^2 = 10^{-4}$ erg cm^{−3} s<sup>−1}. The **spectral distribution** of coronal emission is also T-dependent: at 1–2 MK, lines of Fe IX (171 Å), Fe XII (195 Å) etc. dominate (EUV). At 10 MK, free-free X-ray continuum and Fe XXV (6.7 keV line) appear. The code can use a simplified approach: for a given *T*, choose a representative color (e.g. use the peak line's wavelength or a blend). For instance, at 1 MK, color the loop in EUV ~171 Å; at 2 MK use 195 Å; at 10 MK use soft X-ray ~10 Å. The **radiative power loss** globally from quiet Sun corona is ~8×10⁵ erg cm^{−2} s^{−1} [55] (must be balanced by heating). Active regions output up to an order of magnitude more per area.

Radio Emission Mechanisms: The Sun emits radio waves through several processes, with frequency-dependent characteristics:

- **Thermal free-free emission (Bremsstrahlung):** Dominant in quiet Sun at cm–m wavelengths. This arises as electrons scatter off ions in the chromosphere and corona. It produces an almost flat (optically thin) spectrum at high frequencies and a rising spectrum at low frequencies where the plasma becomes optically thick. The Sun's **brightness temperature** *T_b* at radio frequencies ranges from ~**6000 K at 100 GHz** (3 mm) up to ~**2×10⁵ K at 1 GHz** (30 cm) [56] . Essentially, at high freq (mm-wave), we see the chromosphere (~6000–10,000 K), while at lower freq (dm- to m-wave) we see the corona which has higher T. For instance, measured quiet Sun T<sub>b>: 100 GHz ~ 0.006 MK, 10 GHz ~ 0.02 MK, 1 GHz ~0.2 MK [56] . The spectral flux of the quiet Sun can be approximated by a blackbody at T_b with solid angle ~0.5 deg diameter. In code, one can implement a formula: $T_b(ν) = T_0 \,[1 - \exp(-τ(ν))]$ with optical depth $τ(ν) ~ (ν/ν_0)^{-α}$. For free-free in corona, at low frequencies (~10 MHz) τ >> 1, so T<sub>b>~ T_cor ~ 1 MK; at high ν (~100 GHz) τ << 1, so T<sub>b> ~ T_phot ~ 6000 K. A simpler way: use the empirically derived values – e.g. a fit $T_b(ν) \approx 2\times10^5 \,(\frac{ν}{1~\text{GHz}})^{-0.7}$ K for 0.1–10 GHz range (rough slope from 200,000 K at 1 GHz to ~20,000 K at 10 GHz, matching ${\sim}6,000$ K at 100 GHz) [56] .

- **Gyroresonance emission:** In strong magnetic fields (like active region sunspot coronae), electrons spiraling at low harmonics of the gyrofrequency can produce intense microwave emission. Gyroresonance typically occurs at frequencies where $ν = s \,ν_B$ (cyclotron frequency $ν_B = 2.8$ MHz/G · B). For a sunspot with B ~2000 G, $ν_B≈5.6$ GHz; second harmonic ~11 GHz, etc. Thus, **active regions** often show bright spots at 5–15 GHz due to gyroresonance in low corona. This emission has a high brightness temperature (up to millions K) and is nearly circularly polarized. For code, when rendering a magnetogram to radio, if a region has B above ~1000 G, treat it as a microwave source at those gyro frequencies.

- **Plasma emission (coherent bursts):** During solar flares and eruptions, **coherent radio bursts** occur (Type III bursts, etc.). These are caused by plasma instabilities (electron beams, etc.) generating Langmuir waves that convert to radio at the local plasma frequency $f_{pe}\approx9\,\sqrt{n_e}$ kHz (with n_e in cm^{−3}). Type III bursts, for example, rapidly drift from ~500 MHz down to <1 MHz as electron beams travel outward and encounter decreasing density. Their intensities far exceed thermal levels (T_b ~10⁹–10¹² K). In the simulator, one could include an option for bursts: when a flare triggers, generate a quick frequency drift of bright emission. But this might be beyond a steady visualization – likely not needed unless doing dynamic time-domain simulation.

- **Gyrosynchrotron emission:** Fast electrons in flares (nonthermal distributions) produce broad-band continuum from microwave to decimeter waves via gyrosynchrotron radiation. This results in strong flare radio sources peaking ~1–10 GHz, with T_b up to ~10⁷–10⁸ K. These follow the flare energy release and last minutes. In code, if simulating flares, one can approximate the radio flux increase in e.g. the 1–5 GHz range correlated with X-ray emissions.

In summary, **for real-time rendering**: the quiet Sun's radio brightness can be pre-computed as a function of frequency (using the above $T_b(ν)$ curve) [56], and flare events can overlay nonthermal components. If the simulator allows tuning frequency, it can show that at higher frequencies you see primarily the chromosphere (with sunspot-associated gyro sources), while at low frequencies you see the extended corona (appearing larger than optical disk, with limb brightening due to optically thick plasma emission near the limb and over active regions) [50].

Transient Phenomena & Dynamics

Magnetic Reconnection & Solar Flares: Solar flares occur when stored magnetic energy (in stressed coronal field) is suddenly released via reconnection. A large X-class flare can release **~10^32 ergs** (10^25 J) of energy in a few minutes [57] [46]. The reconnection process is often modeled by the **Sweet-Parker or Petschek** regimes. Typical **reconnection inflow speeds** in flares are on the order of 0.001–$0.1\,V_A$ (Alfvén speed). In high-$β$ current sheets, Petschek fast reconnection can approach ~0.1 V_A. For example, if $V_A ~ 1000$ km/s, inflows of ~100 km/s and outflows ~1000 km/s are possible. Observationally, **flare ribbon separation speeds** (related to reconnection rate) are tens of km/s, and **HXR loop-top source motions** suggest upward reconnection outflows ~1000 km/s. One direct measurement found a coronal field in a flare decaying at ~5 G/s over 2 minutes in a volume ~10²⁸ cm^3, implying an average **magnetic energy conversion rate** of ~10^27 erg/s [58] [38].

For code, one can include a **reconnection scaling**: e.g. set reconnection electric field $E \sim V_{in} B \sim 1$ V/m for large flares (this drives particle acceleration). The **energy release curve** of a flare typically shows a rapid rise to peak over ~1–5 minutes followed by a slower decay over tens of minutes (often exponential fall-off). A convenient parametric model is a *skewed Gaussian or exponential pulse*. For instance: $P_{\text{flare}}(t) = P_0 \exp(-(t-t_0)/\tau_r)$ for rise (τ_r ~ 1 min), and $P_{\text{flare}}(t) = P_{\max} \exp(-(t-t_{\max})/\tau_d)$ for decay (τ_d ~ 5–15 min), matching observed soft X-ray lightcurves. We might instruct the code with **energy partitions**: of the total ~10^32 erg, ~10–20% goes into thermal plasma heating (seen in X-rays/EUV), another ~10–50% into nonthermal electrons (HXR bursts), etc. But for visualization, focusing on thermal emissions (bright flare loops in EUV/X-ray) and optical/UV ribbons is sufficient. The **magnetic reconnection region** in a flare often produces a cusp-shaped post-flare loop arcade with a **current sheet** above it; a high-density, bright **flare loop** forms (footpoints at chromosphere give **flare ribbons**). If needed, Claude can be given the standard CSHKP model geometry to draw these loops.

Coronal Mass Ejections (CMEs): A CME is the eruption of a large magnetic structure and plasma into interplanetary space. Key parameters:

- **Mass:** typical 1×10¹⁵–1×10¹⁶ g (billions of tons).

- **Velocity:** widely varies. **Average ~489 km/s** [59]; slow CMEs ~300–400 km/s, fast CMEs ~1000–2500 km/s. Extremes up to ~3500 km/s have been observed [60]. The speed *profile* usually involves **acceleration near the Sun** (within a few solar radii) and then approximately constant speed in the solar wind (fast CMEs may decelerate if they exceed solar wind speed, slow CMEs accelerate slightly). For simulation, one can animate a CME lifting off with a rising speed profile e.g. $v(r) \approx v_{\max}(1 - e^{-a r})$ reaching ~80% of $v_{\max}$ by say 5 R_⊙.

- **Angular Width:** CMEs can be narrow jets (<20° angular span) or wide. The largest are **halo CMEs** (360° width, as they surround the occulting disk). **Typical CME angular width** is ~60° for normal CMEs, with some **partial halos ~120°** and **full halos ~10%** of events [61]. Statistically, mean width ~85–100° [62] [63]. The code can classify: "narrow CME" if width <30°, "normal CME" ~60°, "halo" ~360°. Often, width correlates with speed (fast CMEs tend to be wider) [64].

- **Morphology:** Classic CMEs have a **3-part structure**: a bright leading front (compressed plasma/sheath), a dark cavity (magnetic flux rope cross-section), and a bright core (embedded prominence) [65]. In coronagraph images, this appears as an expanding loop. For visualization, one can model a CME as an expanding torus or flux rope. The **prominence core** might be cooler (~10⁴ K) filament material – in EUV, it appears as a bright core, and in Hα as an erupting filament. The leading front is shock/compressed wind if fast. The **angular span** is filled by this loop shape.

- **Kinematics:** A simple empirical velocity profile: a rapid acceleration phase (for impulsive CMEs, acceleration ~0.1–1 km/s^2 for a few minutes) followed by coasting. Some slow CMEs accelerate gradually over hours (e.g. 1–5 m/s^2). If not explicitly simulated, one can just assume an average constant speed once visible in corona. For example: a CME starting at 1 R_⊙ at 100 km/s and reaching 1000 km/s by 5 R_⊙.

To include CMEs in a simulator, provide an option to "launch" a CME from a given active region: specify an initial direction and angular width, plus a velocity. The code can then create a time-dependent expanding loop structure with the above characteristics. **Scaling for other stars:** CME frequency and mass might scale with stellar magnetic activity (e.g. more active stars could have more frequent or massive CMEs). For our scope, using solar values is fine, but see Stellar Variation for adjustments (e.g. a young active Sun might produce more frequent CMEs).

Prominences/Filaments: Prominences are cool, dense plasma (10⁴ K, 0.1–0.001 g/cm^3) suspended in the corona by magnetic fields. When seen against space beyond the limb, they appear bright (Hα emission structures); against the disk, they are **filaments** (dark absorption features in Hα). Key parameters:

- **Size:** Prominences are huge – **lengths** can be 5×10^4 km up to **~200,000 km**. The largest recorded prominence stretched >800,000 km (roughly the Sun's radius) [66] [67]. Typical length for a quiescent prominence might be 50,000–100,000 km. **Width/thickness** ~5,000–10,000 km (with fine substructure <1000 km threads). They often form arched sheet-like structures. The **height** above the photosphere can be 20,000–50,000 km for quiescent ones; active region prominences are lower (10,000–20,000 km).

- **Lifetimes: Quiescent prominences** (forming outside active regions, at higher latitudes) can last **weeks to months** (often persisting through a solar rotation ~27 days) [68] [69]. They are relatively stable, sustained by magnetic dips. **Active prominences** (associated with sunspot regions) are short-lived, **minutes to hours**, often erupting or collapsing in a flare/CME [70].

- **Dynamics:** Prominences are not static – they have flows along magnetic threads (5–50 km/s) and oscillations. When they erupt (often becoming the core of a CME), their rise velocity can be 100–300 km/s. In quiescent state, **internal flows** of ~10 km/s are common. Occurrence: dozens of filaments may be on the Sun at a given time, especially during cycle maxima. At any time, at least a few large filaments (length > 30° in longitude) are usually present on the disk.

To simulate a prominence, one could instantiate a suspended slab or dipped filament channel with a certain length and height, anchored at both ends in opposite polarity regions. **Thermal properties:** cool core ~10,000 K (visible in Hα, Lyman lines), surrounded by transition region sheath at ~10⁵–10⁶ K. Visualize in two ways: (1) as a dark filament on disk in Hα (or extreme UV absorption), and (2) as a bright feature beyond limb when backlit by corona. For numerical values, a prominence might be given a density ~10⁻¹⁴ g/cm^3 (100x denser than ambient corona) and temperature 10,000 K for core.

Spicules: Spicules are dynamic jet-like features that permeate the chromospheric network. They are essentially **grass-like plasma jets** shooting up from the chromosphere. Parameters:

- **Height:** reach **5,000–10,000 km** above the photosphere for classical Type I spicules [71]. Newer "Type II" spicules (rapid, in coronal holes) can reach up to 10,000–15,000 km before fading.

- **Diameter:** ~300–1000 km (they are thin tubes).

- **Velocity: Upward speeds ~20–30 km/s** for average spicules [72]. Some spicules (Type II) exhibit **~50–100 km/s** upward motion [73]. After reaching max height, they either fall back or dissipate. Downflows can be slightly slower.

- **Lifetime:** short – **3 to 10 minutes** is typical [73]. Type I spicules ~5-7 min, Type II often <3 min. They are continuously generated (hundreds appear each minute across the Sun).

- **Occurrence rate:** It's estimated that at any given time, ~60,000–100,000 spicules are present on the Sun. Essentially, they carpet the chromosphere, especially around network cell boundaries. Each spicule might last ~5 min, so to maintain steady state that many must be launching per minute globally.

For simulation, spicules can be treated statistically or via an emissivity boost in chromospheric network regions. A practical approach: every few minutes of simulation time, spawn a bundle of spicule jets at random network positions with given velocity profile (e.g. rise for 50 s at 25 km/s to 5000 km, then fade). They can be rendered as thin, bright Hα features. The **temperature** in spicules transitions from ~5000–8000

K at base to ~20,000 K at top (some spicules even reach transition region temps ~0.1 MK) [74]. But since they are dense, they appear dark in coronal EUV images (absorbing background) and bright in chromospheric lines.

Flares, CMEs, Prominence Eruptions Combined: Often these phenomena are linked (the **eruptive flare** paradigm): a flare happens as a CME lifts off, and an active-region prominence erupts simultaneously. In a comprehensive simulator, triggering one could result in all: e.g. user triggers "X-class flare", the code produces a flare loop brightening (X-rays/EUV), plus launches a CME and shows a filament lifting. The energy-time profile of the flare can be tied to CME acceleration (impulsive acceleration correlates with flare impulsiveness). For our data: an X-class flare ($\sim10^{32}$ erg) usually is accompanied by a fast CME (~1000 km/s) and a sizable filament eruption. A weaker C-class flare ($\sim10^{30}$ erg) might have no CME or a slow narrow one.

Stellar Variation Presets & Scaling

To extend the solar simulator to other star types, we define a `StellarParameters` structure that holds fundamental parameters and specific effects (like granule size, cycle period, etc.). Key fields can include:

- `mass` (M_⊙), `radius` (R_⊙), `luminosity` (L_⊙), `T_eff` (effective temperature in K), `log_g` (surface gravity),
- Interior structure indicators: `convective_envelope_fraction` (by mass or radius), `differential_rotation_profile` (e.g. coefficients A, B, C for Eqn above),
- Magnetic/dynamo: `activity_level` (e.g. sun=1, a younger star might be >1), `cycle_period` (years, 11 for Sun if cyclic, or 0 if none),
- Granulation: `granule_size` (km), `granule_lifetime` (s), possibly `granule_count_estimate`,
- Supergranulation: `supergranule_size` (km), `supergranule_velocity` (m/s),
- Eruptive phenomena: typical flare energy range, CME occurrence rate.

We populate this for a selection of presets:

1. Sun (G2V, 1 M_⊙): *(Baseline)*

- `mass=1.00`, `radius=1.00`, `luminosity=1.00`, `T_eff ≈ 5778` K.
- Convective envelope spans outer 30% by radius (0.0003 M_⊙ convective mass). Radiative core 70% radius.
- Differential rotation: $Ω(φ)=14.713 - 2.396\sin^2 φ -1.787\sin^4 φ$ (deg/day) [27].
- Granules: ~1000 km cells, lifetime ~8 min, speed ~2 km/s (vertical).
- Supergranules: ~30,000 km cells, 24 h lifetime, ~0.3 km/s flows [24].
- Magnetic cycle ~11 yr, moderate activity (sunspot coverage ~0.1% at peak). Polar field ~10 G flips every cycle [46]. Typical large flare ~10^32 erg once per 10 years (X-class), more common C-class (~10^30 erg) flares monthly during max.
- CME: ~1 per day at solar max (few per week average), speeds 400–1000 km/s typically, mass ~10^15 g.
- Spots: up to 3000 G umbra [39]. Surface magnetism average ~1 G (quiet Sun).
- Limb darkening: e.g. $I(μ)/I(1) = 0.3 + 0.93μ -0.23μ^2$ at 550 nm [47] (coeffs vary vs λ as given above).

2. F-type Dwarf (e.g. F5V, 1.3 M_⊙):

- `mass≈1.3`, `radius≈1.2`, `luminosity≈2.5` L_⊙, `T_eff≈6600 K` [75] [76]. (An F0 would be hotter ~7400 K, 1.7 M_⊙, 6 L_⊙).
- Much smaller convective envelope: a late-F star still has a thin convective layer (~5–10% by radius). Earlier F (T_eff >~7000 K) becomes mostly radiative envelope (tiny convective zone).
- Thus, **granulation** is present but cells are smaller and lower contrast (higher *g* and lower opacity). Granule size scales roughly with pressure scale height H: for F5, log g ~4.2 (vs Sun 4.44), so H is a bit larger – granules perhaps ~1500 km. Lifetimes similar or slightly shorter (~5 min) since higher T increases sound speed.
- **Differential rotation:** F-stars often rotate faster (many F5 have P_rot ~ days). If not tidally braked, an F5 might have equator period ~3–10 days. Observations show differential rotation stronger in higher-T stars (due to shallow conv. zones): e.g. a young F star might have ΔΩ up to 0.1 rad/day. For simplicity, use solar-like law but adjust amplitude: e.g. equator ~20°/day, poles ~16°/day (if known, use observed values for an F-type).
- **Magnetism:** Because of thin convective zone, older F stars have weaker dynamos and often less frequent large spots (many are more chromospherically quiet). However, young F stars (rapid rotators) can be very magnetically active (with starspot coverage a few percent and short cycles or irregular cycles).
- Let's assume a moderate case: **activity**: perhaps cycle period ~<10 yr or irregular, starspot fields ~2000 G but covering small fractional area (except in rapid rotators where they form polar spots).
- **Limb darkening:** Hotter stars have stronger limb darkening in blue but also more flux in blue. At 6600 K, an approximate linear limb darkening coefficient u ~0.5 at 500 nm, 0.2 at 1000 nm. We could provide a specific law (e.g. for F5: $I(\mu)/I(1) \approx 0.1 + 0.9\mu$ in V-band as a rough fit).
- **Flares/CME:** F-type stars of solar age are not known for strong flares (those are more a feature of cooler red dwarfs). But if it's a young active F, it might produce flares (some early F have been observed flaring in UV/X-ray). For code, one can allow flares but at lower frequency than for cooler dwarfs. CMEs likely occur but not well-studied; assume comparable energy to solar or a bit higher maximum (but overall occurrence maybe less if magnetic activity is less frequent).
- Overall, an F5V in the simulator would appear somewhat **brighter and whiter** than the Sun, with perhaps fewer spots and a weaker cycle (depending on chosen age).

3. G2V – Sun: (Already given above, just noting it as the reference preset with all parameters filled – it should be the most detailed and used as default.)

4. K5V (0.7 M_⊙ dwarf):

- `mass≈0.74`, `radius≈0.70`, `luminosity≈0.20` L_⊙, `T_eff≈4100 K` [77] [78]. Example: 61 Cyg A is K5V with very similar values.
- **Convection:** K stars have **deep convective envelopes** (a K5 has convective zone reaching ~0.4–0.5 M_⊙ in mass, i.e. most of star except core). This leads to efficient dynamos.
- **Differential rotation:** Observations of K dwarfs show differential rotation similar or slightly less shear than Sun, but rotation periods can be variable. Suppose a K5 has P_rot ~30 days (older one) or shorter if younger. We can keep solar differential rotation law for simplicity or moderate it slightly. If needed, A=14°/day, B=-2°, C=-1.5°/day (just a minor tweak).
- **Granulation:** cooler T means higher opacity, larger granules relative to star? But also surface gravity is slightly lower (log g ~4.6 for K5), so scale height a bit bigger relative to radius. Possibly granules

are a bit larger in physical size (~1500 km) and lower contrast (due to molecule blanketing). However, empirical intensity contrast on K dwarfs is not well measured; we can assume similar or slightly lower contrast.
- **Magnetic activity:** K dwarfs can be very magnetically active (e.g. ε Eridani, K2V, has a cycle and more UV emission than Sun). Many K5 have strong chromospheric emission (Ca II H&K) and flares. **Cycle periods** observed in some: e.g. 61 Cyg A (K5V) has an ~7-year cycle. We might set cycle ~~8 years for this preset. Spot coverage at max could be similar to Sun or a bit higher (0.2%). Starspot latitudes may extend further (because lower T means higher latitude spots are possible).
- **Flares:** smaller mass stars often flare more frequently relative to quiescent output (though peak energy maybe lower than in bigger stars). A K5 can produce flares of at least ~10^32 erg (if very active) and many ~10^30 erg events if young. E.g. binary K dwarfs are known to flare.
- **CMEs:** Possibly more frequent per unit area due to stronger fields, though not directly observed. We will assume similar CME properties scaled down a bit (maybe average speed 400 km/s, but not much data – we keep solar-like).
- **Spectral features:** strong molecular bands (TiO) appear in K5 spectrum, making limb darkening more pronounced in some bands. This star would appear orange; its limb darkening coefficient in V band might be *u* ~0.7. We could supply: e.g. $I(\mu)/I(1) = 0.4 + 0.8 \mu - 0.2 \mu^2$ as a plausible fit.

5. M3V (0.3 M_⊙ red dwarf):

- `mass≈0.35`, `radius≈0.38`, `luminosity≈0.015` L_⊙, `T_eff≈3300 K`. (From interpolation: M0 0.5M⊙,0.6R⊙,0.1L⊙; M5 0.21M⊙,0.21R⊙,0.01L⊙ [79], so M3 ~0.3M⊙,0.4R⊙, 0.02L⊙.)
- **Convection:** Late M dwarfs (≥M3) are **fully convective or nearly so**. M3 might still have a tiny radiative core, but for modeling we can consider it fully convective. This means the dynamo mechanism may be distributed (no tachocline). Observationally, many mid-M stars show magnetic activity (flaring, strong flares if fast rotation), but the presence of a structured cycle is uncertain – it might be more irregular. For simplicity, we can set **cycle_period ~ not well-defined** or long (some models predict long cycles or none; some M dwarfs show cycles of a few years in chromospheric emission, but data is sparse).
- **Differential rotation:** Fully convective stars might rotate more rigidly (some models predict little latitudinal shear). We could simplify and say differential rotation is **minimal** (the code could just spin the M star almost like a solid body, or a very small difference between equator and pole). If needed, use A ~ some rad/day and B, C ~ near 0. For example, if rotation period is 60 days (older M dwarf), equator ~6°/day, pole ~5.8°/day (just ~3% difference). Young fast M dwarfs often are rapid rotators (P ~ days) but let's assume a middle-aged one with moderate rotation.
- **Granulation:** The photosphere of M3 is cool (~3300 K) and dominated by molecules (TiO, etc.), making opacities complex. Numerical 3D models indicate **granules are larger relative to star** – and since the star is smaller, absolute granule size could be similar (a few hundred km to 1000 km), but covering a larger fraction of the disk. Also, contrast is lower because radiative flux is lower (the convective efficiency is high, so less stark difference between granule and lane temperatures). We might choose granule size ~700 km for M3, lifetime ~5 min.
- **Magnetic fields:** Many M dwarfs have very strong average fields (e.g. 1–3 kG over entire surface) if they are active. Even slowly rotating M dwarfs can maintain strong fields due to distributed dynamo. So we can set average field ~100 G (inactive older M) up to 1000+ G (active young M) on surface. Flares on M dwarfs are notorious – e.g. **Proxima Centauri (M5.5Ve)** has flares reaching 10^32 erg even though its luminosity is 0.001 L_⊙ (so relative intensity is huge). Our M3 could have

frequent flares, including giant “superflares” of 10^33 erg possibly. If it’s a “flare star” like UV Ceti (M5), flares happen daily to weekly.

- **CMEs:** Fully convective stars might produce frequent CMEs (each flare might eject mass). Some theoretical scaling suggests active M dwarfs could lose significant mass in CMEs. In absence of direct data, we can assume CME rates 10x solar and speeds ~300–500 km/s (escape velocity of an M3 is lower ~400 km/s, so CMEs need not be extremely fast).
- **Visual appearance:** M3 star would be **red-orange**. Limb darkening is very strong in visible (because most flux comes from deep where T is higher, and outer layers have low continuum opacity but molecule opacity in lines). Possibly u ~0.8 in V-band. The star would be much dimmer per area than Sun; but if viewer adjusts brightness, they’d see a mottled surface with many starspots (active M dwarfs can have large, high-latitude spots covering 10% of surface). Spots on M dwarfs can be nearly as cool as 2700 K vs photosphere 3300 K, so they cause big brightness dips. We should note: **starspots** on very active M dwarfs can be huge (one spotted M dwarf had a single spot covering 15% of the disk). So for an “active” M3 preset, instruct to include big dark areas (and potentially flares brightening small regions tens of percent).
- **Spectral output:** extremely dominated by red/IR, negligible UV (any UV is from flares or chromospheric emission lines). The code might incorporate that metallic lines blanketing is heavy in optical.

6. Red Giant (e.g. K5 III, ~1.2 M_⊙):

- We pick **Aldebaran** (K5 III) as example: `mass≈1.16 M⊙` [80], currently `radius≈44 R⊙` [81], `luminosity≈440 L⊙` [80], `T_eff≈3900 K` [82].
- **Interior:** Red giants have an **inert Helium core** (contracting) and a very large convective envelope. Virtually the entire star outside the core is convective (for K5III, the convective envelope ~40 R⊙ deep!). So it’s like a scaled-up convective star. No differential rotation data (likely nearly solid-body rotation at slow rate, because giants spin slowly, P_rot ~ couple hundred days or more due to expansion). We can assume **solid-body rotation** or extremely small ΔΩ. If needed, use A ~2°/day, B,C ~ 0 (just conceptual; actual rotation of Aldebaran is ~ slow, v~5 km/s at surface, period ~520 days).
- **Granulation:** As discussed, **few, giant convective cells**. 3D models and interferometry of π^1 Gruis (a 350 R⊙ red giant, similar class) show only ~a dozen granules on the surface [25] [83]. Each cell can be enormous: π^1 Gruis had granules covering ~27% of the stellar diameter (~0.27 * 350 R⊙ ≈ 95 R⊙ across!) [83]. Aldebaran is smaller (44 R⊙), so its convective cells might be smaller in absolute terms, but still on order 10 R⊙ (maybe a few cells tens of percent of disk). So one might implement e.g. ~5–10 giant cells that evolve on timescales of weeks to months [84] [85]. Underlying those large cells, there are also smaller granular structures but with lower contrast [86] – however, the dominant observable effect is the large patches. So for visualization, showing a blotchy surface with 2–3 large hot cells and surrounding cooler regions suffices.
- **Pulsations:** Many red giants are variable (semi-regular or Mira variables). The code might incorporate a fundamental pulsation period (like Aldebaran is slightly variable ~0.2 mag). Periods can be ~months. But if focusing on convection, can omit pulsation unless desired.
- **Magnetic fields:** Red giants generally have weaker magnetic activity than dwarfs of same T (because rotation slows). However, some do show starspots and cycles (e.g. HK project saw cycles in some giants). If any, cycle periods are long or irregular. We can assume **low activity**: e.g. starspots covering <1% sporadically, flares rare. (However, note that supergiants can have large convection causing surface activity, but it's more mass-loss oriented than flares).

- **Mass loss:** Giants have **slow dense winds** (Aldebaran's mass loss ~$1\times10^{-11}\ M_\odot$/yr). In simulation, this could appear as a constant outward flow from the star (but optional to render).
- **CMEs:** Not well documented, but likely giants eject material in more continuous manner (or large blobs due to convective cell tops). Possibly treat them as irregular outflow rather than discrete CMEs.
- **Limb darkening:** Very cool effective T ~3900 K, and giant log g ~1.5, so limb darkening is *weak or even limb brightening*** in molecular bands because of extended atmosphere. Usually, continuum limb darkening for giants is small (limb might be only slightly dimmer than center, or even some wavelength show bright limb due to chromosphere). For simplicity, we can set a mild limb darkening law: e.g. $I(\mu)/I(1) \approx 0.5 + 0.5\mu$ (just linear with u=0.5) in V-band. The code could also incorporate the extended atmosphere by not having a sharp limb (some optical depth at $R>R_{star}$ causing a diffuse limb).
- **Granulation contrast:** huge cells means star's disk could show large "spots" of different brightness (not magnetic spots, but convective). E.g. π^1 Gruis images showed ~ hundreds K temperature difference cells [87]. The simulator can implement ~10% intensity variation patches.
- **Spectral output:** dominated by IR; lots of molecular absorption (TiO, CO). The star looks very orange-red. Chromosphere exists (as evidenced by Ca II emission in some giants), but overall UV output is low.

7. Blue Supergiant (e.g. B8 I, 20 M_⊙):

- Example **Rigel** (β Orionis, B8 Iae): `mass≈20 M⊙` [88], `radius≈78 R⊙` [89] [90], `luminosity≈1×10^5 L⊙` [89], `T_eff≈12,000 K` [89]. (Some sources say 66,000 $L_\odot$, others up to 120,000 $L_\odot$ – it's in that range).
- **Structure:** A blue supergiant is a post-main-sequence massive star (Rigel was likely ~O-type main sequence). It has a **He-burning core** maybe, with a stratified envelope. The envelope is mostly **radiative**; however, massive stars have subsurface convection zones from iron opacity bump that can cause small-scale convection (not visible as granulation, but may cause micro-turbulence). Overall, expect *no large convective cells on surface* (the star is too hot and envelope stable except for possibly small convective zones ~1% radius). Instead, these stars may exhibit **non-radial pulsations** and **strong radiatively driven winds**.
- **Rotation:** Many B supergiants rotate moderately fast (Rigel's v sin i ~40 km/s). Period could be on order of few tens of days for a 78 R star (if 40 km/s at equator, period ~100 days). Differential rotation is not measured; assume nearly solid rotation (and anyway a radiative envelope would not have the same dynamo-driven shear as Sun). We set it as rigid for simplicity.
- **Magnetism:** Only a minority of massive stars have strong fields (the so-called **magnetic OB stars** with ~kiloGauss fields); if present, they channel winds and produce hard X-rays. But Rigel is not known to have a strong field. Generally, expect **no sunspots or cycles** on a normal blue supergiant (they lack a convective dynamo). For code, we might turn off starspot and cycle modules. If a user specifically wants a "magnetic Bp star", that's a special case not in our main presets.
- **Surface phenomena:** Instead of granulation or spots, **FeII-line pulsations** or **κ-mechanism pulsations** can cause surface brightness variations at the few percent level on timescales of days (some BSGs are Alpha Cygni variables). Additionally, **wind clumping** can cause stochastic variations in UV lines.
- **Limb darkening:** Hot star, large radius, lower log g (~1.75 for Rigel). Limb darkening in continuum could be significant (u ~0.3–0.4) but the extended atmosphere and electron scattering can cause a more uniform brightness distribution. We might choose an intermediate: $I(\mu)/I(1) = 0.4 + 0.6\mu$ for visual light.

- **Mass loss:** Blue supergiants have strong winds (Rigel's mass loss ~10^-6 M⊙/yr with v∞ ~600 km/s). In visualization, this could be depicted as a continuous outflow or a big extended atmosphere.
- **Emission:** The star's spectrum peaks in the UV. It will have strong ionizing flux – but simulation wise, that means the star will look bluish-white. If simulating UV view, you'd see lots of wind lines (NV, SiIV). But presumably we focus on optical appearance.
- **Transient events:** No flares (these stars don't do magnetic reconnection flares). However, **eruptions** like LBV outbursts can happen in more luminous ones (not so much Rigel, but e.g. Eta Carinae). Those are more like massive discrete mass ejections over months (could be analogous to giant CME but driven by something else). We likely skip that.
- So in summary, the B supergiant preset: **no starspots, no cycle**. Possibly include *line-driven wind* effect (the star could have a bright corona-like wind region but at much lower density and not confined by B, so maybe not visible aside from spectral lines). Possibly include some *pulsation*: e.g. a 10-day period small radius variation causing ~0.1 mag change.

8. White Dwarf (e.g. DA, 0.6 M_⊙):

- Typical: `mass≈0.60 M⊙`, `radius≈0.012 R⊙ (≈1.1×10^4 km)` which is ~Earth-sized [91]. `Luminosity` – when newly formed (T ~100,000 K) it could be ~0.1 L⊙, but a 0.6 M⊙ WD after 1 Gyr of cooling at **T_eff ~10,000 K** has `L ~0.001 L⊙` [92]. Let's set **T_eff ~10,000 K** (cooling age ~0.3 Gyr).
- **Structure:** The WD is basically a dense electron-degenerate core (C/O). No internal energy source; it cools over time. It has a very thin atmosphere (H/He layer).
- **Convection:** If T_eff > ~12,000 K, the atmosphere is radiative; below that, the outer layers become convective (for H atmosphere). But even then, the convection is only in a shallow layer. There is **no large-scale convection pattern visible** – WDs are too small and the convection is beneath a thin radiative photosphere. So effectively, no granulation visible (granules would be tiny and below resolution).
- **Rotation:** Many single WDs rotate slowly (hours to days). A 0.6 M WD might have P ~ days. With no fluid surface (the atmosphere is still gas, but the body is solid-like in terms of not having differential rotation), we can consider it rotating as a solid sphere. So no differential rotation or latitudinal variation.
- **Magnetic fields:** ~10% of WDs have strong fields (10^5–10^9 G). But a typical DA has maybe ~10^3 G or less, essentially unobservable. If we choose a non-magnetic WD, there are no spots or cycles – no dynamo at work. If we wanted, we could add a magnetic WD preset separately. For now, assume not strongly magnetic.
- **Surface features:** None in normal light. A WD is a point-like smooth disk (angular size tiny). In our hypothetical simulator, if we "zoom in" ridiculously (WD of 10^4 km diameter), one might ask if there are any inhomogeneities – likely not, unless it's magnetic (which can cause dark spots where B suppresses convection, analogous to starspots, observed in some highly magnetic WDs as rotating intensity modulation). But standard WD: featureless. Possibly *pulsations*: Many WDs (DAV, DBV) pulsate with periods ~100–1000 s at millimagnitude amplitudes. If we include that, it would be an overall brightness oscillation of the star, not surface pattern.
- **Limb darkening:** High gravity (~log g 8) and pure hydrogen atmosphere yields significant limb darkening. Model atmospheres give e.g. for a DA, *u* might be ~0.4–0.5 in visible. We can use $I(\mu)/I(1)=1 - 0.5(1-\mu)$ for simplicity.
- **Spectral output:** Peaks in UV/blue for 10,000 K. Quite blue-white. Over time WD cools to redder. Ours at 10,000 K still emits a lot of UV. But faint in luminosity total.

- **Flares/CMEs:** None – WDs don't have conventional flares (no magnetic corona). (If accreting, they can have dwarf novae, but that's another scenario).
- The simulator for WD would likely just show a small bright dot. If we artificially enlarge it to see limb darkening, one might see a uniform disk with limb darkening, but no other surface detail. If a pulsating WD, maybe global blinking at a known period.

Summary Table – Stellar Presets:

For direct use, here's a structured list of the key parameters for each type, which Claude Code can incorporate as defaults:

Star Type	Mass (M⊙)	Radius (R⊙)	Luminosity (L⊙)	T_eff (K)	Convective?	Rotation & Dynamos	Surface Features	Other Notes
F5 V (1.3 M⊙)	1.3	1.2	2.5 [75]	6600	Shallow conv. zone (15% R) – mostly radiative	Prot ~5–10 d if young; differential rot ~ solar or slightly higher shear. Dynamo present if rot fast. Cycle uncertain.	Granules ~1–2 Mm (slightly larger than Sun); fewer spots unless young (spots mainly low latitudes). Limb darkening strong (u~0.5 in V).	UV bright, moderate winds (few×10^-14 M⊙/yr).
G2 V (Sun)	1.00	1.00	1.00	5778	Convective envelope (30% R, 2% mass) [9]	Prot ~25d, differential rot: A=14.7, B=-2.3, C=-1.8 (°/day) [27]. α–Ω dynamo, 11-yr cycle.	Granules ~1 Mm, 8 min; supergranules 30 Mm, 24h [24]. Sunspots (umbra 3 kG) cover ~0.1% area at max.	Regular flares (C to X class); CME ~1/week. Limb darkening: $I(\mu)=0.3+0.93\mu-0.23\mu^2$ [47].

Star Type	Mass (M☉)	Radius (R☉)	Luminosity (L☉)	T_eff (K)	Convective?	Rotation & Dynamos	Surface Features	Other Notes
K5 V (0.7 M☉)	0.74 [78]	0.70 [78]	0.20 [78]	4100	Deep convective env. (~50% mass).	Prot ~30d (older) to <10d (young). Strong dynamo if rotating. Possibly shorter cycle (~7–10 yr) if active.	Granules ~1.5 Mm (slightly larger, fewer than Sun). Spots can be prominent (active K dwarfs have ~1% spot coverage, often high latitude).	Flares common if young (dMe-like behavior when very active). Spectrum very orange (TiO bands). Limb darkening u~0.7 (V).
M3 V (0.3 M☉)	~0.35	~0.38	~0.02	3300	Fully convective (dynamo of different type).	Prot can range days (if young) to months (old). Likely nearly rigid rotation (little diff rot). No Sun-like cycle; activity can be continuous ("flare star").	Granules ~0.5–1 Mm but low contrast. *Entire surface magnetically active:* Starspots huge (covering up to tens % if fast rotator, polar spots common).	Very strong flares (frequent 10^30–10^32 erg). CMEs possibly frequent. Star is red; most emission IR. Limb darkening strong in optical (u~0.8).

Star Type	Mass (M☉)	Radius (R☉)	Luminosity (L☉)	T_eff (K)	Convective?	Rotation & Dynamos	Surface Features	Other Notes
K5 III (Red Giant)	1.2	44	440	3900	Envelope fully convective.	Prot ~ slow (years); essentially solid-body. Dynamo weak or none (if slow rot).	**Very large granules:** only a few (~2–8) cells on surface, each ~10–20% of star's radius [25] [83]. Surface looks patchy, no small granulation. Starspots not from dynamo, but large convective areas cause brightness variation.	Semi-regular pulsations (period ~ months). Steady mass loss wind (~10^-11 M☉/yr). Limb darkening mild (extended atm; u~0.3).
B8 I (Blue SG)	20	78	1×10^5	12,000	Mostly radiative envelope (tiny conv zones near Fe opacity zone).	Prot ~tens of days (if v~40 km/s). Assume rigid rot. No global dynamo (if no conv., unless fossil field).	No granulation visible. Possibly subtle non-radial pulsation patterns (low amplitude). No starspots (unless rare strong fossil B-field which is separate case).	Strong radiative wind (~10^-6 M☉/yr, v~500 km/s). UV-luminous, often bright emission lines (from wind). Limb darkening moderate (u~0.4).

Star Type	Mass (M⊙)	Radius (R⊙)	Luminosity (L⊙)	T_eff (K)	Convective?	Rotation & Dynamos	Surface Features	Other Notes
DA White Dwarf	0.60	0.012	0.001	10,000	Essentially no convection (if T_eff ~10k, top of atm might start convecting, but negligible).	Rot ~ hours-days, rigid. No dynamo (compact object; possible fossil B in some, but assume non-magnetic).	Featureless disk. No granules or spots. (Magnetic WDs would have spot-like hot/cold regions, but not for a standard DA.)	Cooling, will fade. Possible 500s oscillations if pulsating DA (small amplitude). Limb darkening noticeable (u~0.5).

Each of these presets can be loaded into the simulation's `StellarParameters`. The **scaling relations** to interpolate between types would consider:

- **Mass & Radius:** main-sequence mass-radius roughly $R \propto M^{0.8}$ for F-K, steeper for M (see table above for a few points). For luminosity, $L\propto M^{3.5}$ for mid-range, but deviates at lower masses.
- **Effective Temperature:** decreases with mass on MS (except very low mass where it flattens out around 3000 K for 0.1–0.3 M⊙). So an interpolation can use, say, a polynomial or piecewise: (1 M⊙, 5800 K), (0.75 M⊙, 4200 K), (0.5 M⊙, 3500 K), (0.2 M⊙, 2800 K) [77] [79] .
- **Convective fraction:** stars above ~1.2 M⊙ have negligible convective envelope (so set convective_envelope_fraction→0 for A–B stars). From 1.0 M⊙ down to ~0.35 M⊙, convective envelope mass fraction goes from a few % up to ~100%. A simple fit: for M>0.35, convective_mass_fraction ~ $\max(0,\,1.2 - 3.3M)$ (so ~0 at 1.2 M⊙, ~0.5 at 0.5 M⊙, ~~1 at 0.36 M⊙).
- **Differential rotation:** likely a function of T_eff and rotation period. The Sun's shear ~0.2 µrad/s. Rapid rotators might have more shear in absolute terms but maybe less fractional. We could simplify: *if convective envelope present*, use solar profile scaled by (rotation period / 25d)^-1 perhaps. If fully convective, set nearly zero shear.
- **Granule size:** scale with pressure scale height H ~ (k T / µm_p g). Roughly, $H \propto T / (g)$ (since µ ~ constant ~1 for ionized, slightly higher for molecules in M star, but within factor 2). So, granule size ~ a few H. For Sun, H ~150 km at surface (but granule size ~10× H because convection rolls extend deeper). For a giant, g is low so H huge (~ scale of whole star) hence few giant cells. We could input formula: granule_diameter ≈ $a \, \frac{T_{\text{eff}}}{g}$ (with a calibrated to Sun: 2000 km = a * 5778K / (274 m/s^2); a ~2000*274/5778 ~95, which if we then plug for other stars in SI units yields something in same ballpark).
- **Supergranules:** observed clearly only on Sun. Possibly exist on other late-type stars with convective envelopes; not well measured. Could assume size scales roughly with stellar diameter (maybe ~30,000 km on Sun corresponds to ~4% of Sun's diameter; apply 4% of star's diameter for star with envelope).

- **Activity level:** If needed, scale with Rossby number (rotation / convective turnover). Younger, faster = more spots, flares. For code, maybe simpler: user can set an "activity" knob.

- **Cycle:** only G-K stars reliably have cycles. F stars might have irregular or no cycles if shallow convective zone; M fully conv might have long/irregular cycles. Possibly parameterize cycle period ~ proportional to rotation period or inverse Rossby. For Sun (Ro ~2) 11yr; faster rotators (Ro ~0.5) sometimes have 2-3 yr cycles. But also some have dual cycles. We can just supply typical known cycles: e.g. 61 Cyc A (K5V) ~7.3 yr, α Cen B (K1V) ~~12 yr, etc. For M dwarfs: put "none" or "sporadic".

Finally, ensure units clarity: use SI units internally (e.g. radius in m, mass in kg) but the given values are in solar units for convenience. The code should multiply by constants ($R_\odot$ = 6.9634e8 m, etc.) as needed. All temperatures in Kelvin. Magnetic field in Gauss or Tesla (1 G = 1e-4 T).

With these structured parameters and relations, Claude Code can construct a robust, physics-based star simulation that adjusts visuals (surface texture, brightness distribution, flares) and numeric outputs (spectra, light curves) as the user toggles star type or slider inputs. Each preset serves as an anchor for interpolation – e.g. for a G8V (between Sun and K5), it can interpolate radius, T_eff, etc., and likewise intermediate behavior in granulation and activity.

Sources: The values and relations above are drawn from standard stellar models and solar observations [11] [77] [39] [27], ensuring physical accuracy for the simulator. The convective cell behavior for giants is confirmed by interferometric imaging [25] [83], and the solar phenomena by spacecraft and observatories [24] [46]. These will allow Claude to verify and further refine the implementation as needed.

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