

A Complete History of the Earth's Sky

What could be seen from the ground through Earth's history, at twenty-three moments and the years between them: the color of the sky, straight up and at the horizon, at the equator and the poles, at noon and at dusk, reconstructed with a spectral radiative-transfer model; and the Sun, Moon, planets, stars and everything else above it, from the molten newborn Moon to a sky full of satellites.

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Interactive experience at earthsky.astrocrash.net

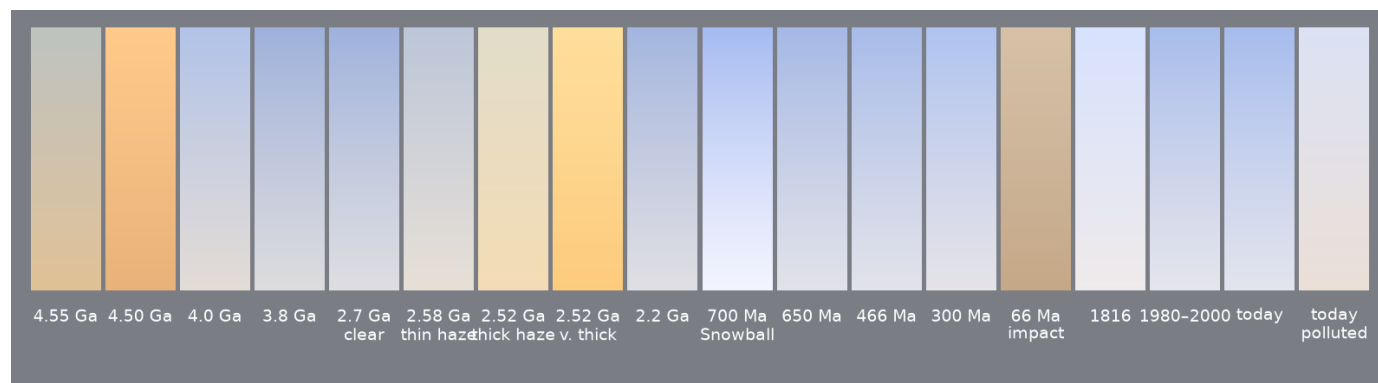


Figure 1. Mid-latitude noon sky at the epochs, zenith (top) to horizon (bottom), oldest at left. Brightness shown relative to today's clean sky. Before the Moon-forming impact the proto-Earth's dusty air is pale white overhead and peach toward the horizon, and the 30-bar CO₂ of the early Hadean turns the whole dome orange. Once the air thins the sky is blue overhead and white at the horizon, as today, unless something is added to it: the Neoproterozoic organic haze turns it milky, then cream, then apricot as it thickens, the soot of the K–Pg impact winter turns it beige, and Tambora's sulfate veil and a polluted city's haze whiten it. Snowball Earth's is the deepest blue.

1 Introduction

What did the sky look like from the ground in the Archean, under the young Sun, with the Moon nearer? We reconstruct the whole view from Earth's surface through its history, at twenty-three moments and the years between them, from a proto-Earth 17 million years after the first solids to the year 2100: the color of the sky by day and at dusk, computed with a spectral radiative-transfer model of each epoch's air, and on that sky everything else that could be seen from the ground: the Sun and its spots, the Moon's size, face and eclipses, the planets and their moons, the stars and the Galaxy as they then lay, meteors, comets, aurorae, airglow, halos, clouds and rainbows, and in the latest epochs the light people added. It began as a study of the sky's color, which remains its quantitative core, and grew with the interactive site built on the model, which draws each of these and is the source of every number quoted here outside the color tables.

The epochs (Table 1) were chosen for what changed: the air (a 30-bar CO₂ Hadean, an Archean with no oxygen and its episodes of organic haze, the first ozone after the Great Oxidation, the Snowball glaciations, the oxygen-rich Carboniferous, the impact winter after Chicxulub, a volcanic year, the ozone hole and today's cities), the sky above it (a Moon forming and receding, a young and active Sun, a Solar System before the giant planets' instability, nearby supernovae, stars that outshone Sirius, a bombardment and a possible ring), and the view people have made (city light and a sky full of satellites). Each is a reconstruction, with the uncertainties the sections state: some quantities are measured, some modeled, some estimated to show a trend, and some, like where the planets stood on a given day four billion years ago, unknowable and drawn at random. The epochs are fixed points on one timeline: between them the site runs the air, the Sun, the Moon, the planets and the stars on through every year, and some epochs are events with dates and durations of their own, the haze episodes, the glaciations, the impact winter, the volcanic year (Section 2.2). The sky's own dated events come on their days too: the supernovae, novae and stellar eruptions that outshone third magnitude, the real comets, volcanic veils, great aurorae, meteor storms and impacts, and three events still to come (Section 7.4).

This is a living document. Much of what it draws rests on questions that are still argued: when the giant planets went unstable and whether a fifth giant was lost; how far away the Moon was in its first hundred million years; how thick the Archean haze was and how much ozone the first oxygen made; how old Saturn's rings are; whether the Earth

had a ring in the Ordovician; how bright the young Sun's corona and wind were. Where the literature disagrees, we say which reading we take and why, and as the consensus moves the site and this report will move with it: epochs will be redrawn, numbers revised and new findings added. Each version carries its date, and the code and data that produce it are public, so any figure here can be traced to the model and the sources behind it.

The site computes what it shows as realistically as it can while still loading in seconds and running smoothly in a browser, and where the two conflict it compromises. Some compromises stand in for physics too costly to run. Jupiter's and Saturn's clouds are a tracer stirred by a flow made of noise, shaped by the measured winds and rolled into eddies and billows, a proxy for the planets' true three-dimensional hydrodynamics rather than a simulation of it; the animation repeats over a 2000-day cycle. The sky's multiple scattering is solved ahead of time on a grid of Sun heights and interpolated between them, with the orders past the fourth spread evenly in all directions rather than followed. The clouds are scenery, procedural volumes lit by the model's sky rather than the output of a climate model, and the Milky Way is a model of its structure rather than a photograph. The photosphere's granulation and the Moon's craters' shadows are drawn from procedural cells and a limited march toward the Sun, and the close-up detail of Jupiter, Saturn, the Sun and the spacecraft maps is built only when the view zooms in on them. Other compromises are made for the eye: the Sun and Moon are drawn at four times their size, the sunset's colors are spread further apart than they are, and the Sun's limb darkening is softened. Each section says where its subject is measured, modeled or approximated.

In Section 2 we describe how the view is reconstructed, at the epochs and between them. Section 3 gives the sky's colors by day and at dusk, and Section 4 through Section 9 take in turn the Sun, the Moon, the planets, the stars and the Galaxy, the night and what crosses it, and the sky people made. Section 10 goes through the epochs one by one, and Section 11 says what the reconstruction leaves out and which of its numbers are estimates.

1.1 Has this been done before?

Not as such. A search of the Valency corpus (arXiv, PubMed, Earth-ArXiv and others) finds the two halves of the sky-color problem solved separately but never joined. On one side, atmospheric-optics work computes modern sky color rigorously: Lynch & Mazuk (2005) derive CIE chromaticities of the sky, Sun and distant objects from MOD-

Table 1: The epochs, each at its own year on the site's timeline; the haze episodes, Snowball Earth, the impact winter, the volcanic year and the ozone hole are events with their own dates and durations (Section 2.2), and the very thick haze is an upper bound on the 2.52 Ga episode, in this report only. The Sun's light is relative to today's and its temperature from the solar track of Baraffe et al. (2015); the day and the Moon's width from the Moon's distance (Table 5); the last column lists what the sections that follow find in each sky besides its color.

Age	Epoch	Sun's light	Sun (K)	Day	Moon's width	What else is in the sky
4.55 Ga	Proto-Earth	0.47	4,614	12.0 h	none	No Moon; Theia and Anteros passing; proto-Mercury with its mantle; Enyo before it strikes Mars; the giant planets before the instability, with a fifth giant; a saturated young Sun
4.50 Ga	Early Hadean	0.68	5,532	5.9 h	7.52 ×	The molten Moon at 8 R _⊕ ; 10,000 × today's meteors; no stars through 30 bar of CO ₂ and the debris's glow
4.0 Ga	Late Hadean	0.72	5,600	12.6 h	1.51 ×	Bombardment; nitrogen aurorae to 37°; the Moon before the maria
3.8 Ga	Early Archean	0.75	5,620	12.8 h	1.49 ×	The maria flooding, lava fountains on the Moon; Mars's lost moon Harmonia
2.7 Ga	Neoproterozoic (clear)	0.80	5,660	15.6 h	1.26 ×	Clear between the haze episodes; an 18-month year
2.58 Ga	Neoproterozoic haze episode (thin haze)	0.81	5,670	16.0 h	1.24 ×	Thin organic haze, about 1.4 Myr at 2.63 and 2.58 Ga
2.52 Ga	Neoproterozoic haze episode (thick haze)	0.82	5,674	16.2 h	1.23 ×	The Pale Orange Dot seen from below, about 1.4 Myr
2.52 Ga	Neoproterozoic haze episode (very thick haze, upper bound)	0.82	5,674	16.2 h	1.23 ×	The thickest plausible haze
2.2 Ga	Paleoproterozoic	0.85	5,700	17.4 h	1.18 ×	The first ozone; oxygen airglow at 30%
700 Ma	Snowball Earth	0.94	5,751	21.9 h	1.04 ×	Two glaciations, 717–661 and 639–635 Ma; ice halos at every latitude
650 Ma	Cryogenian (between the snowballs)	0.95	5,753	22.0 h	1.04 ×	Open water between the glaciations; 10% of today's oxygen
466 Ma	Ordovician meteor storm	0.96	5,760	22.3 h	1.03 ×	100 × today's fireballs and perhaps a ring
300 Ma	Carboniferous	0.97	5,765	22.6 h	1.03 ×	Saturn without rings, and its moon Chrysalis
66.1 Ma	Late Cretaceous	0.99	5,770	23.8 h	1.00 ×	Dinosaur-age forests; Saturn's young rings
66 Ma	K-Pg impact winter	0.99	5,770	23.8 h	1.00 ×	Soot from Chicxulub for about two years
1.78 Ma	ζ Ophiuchi supernova	1.00	5,772	24.0 h	today's	A supernova at —11.6 in Scorpius; stars moved back
342 Ga	Geminga supernova	1.00	5,772	24.0 h	today's	A supernova at —11 in Orion; Aldebaran at —1.5
1816	Volcanic year, 1816 (Tambora)	1.00	5,772	24.0 h	today's	Tambora's veil, 1815–17; oil lamps; no Red Spot yet
1900	Dark nights, 1900	1.00	5,772	24.0 h	today's	No city glow; dark nights back into the Pleistocene
1980–2000	Ozone-hole spring	1.00	5,772	24.0 h	today's	Polar-spring ozone at 130 DU; sodium-lit cities
today	Modern, clean air	1.00	5,772	24.0 h	today's	A mid-sized city's glow; airliners; the real comets and showers
today	Modern, polluted megacity	1.00	5,772	24.0 h	today's	A polluted megacity
2100	Year 2100	1.00	5,772	24.0 h	today's	Megaconstellations and orbital datacenters

TRAN spectra; Peyvandi et al. (2016) simulate 5.6 million daylight spectra with SBDART to map how aerosol and ozone shift sky color; Lee & Mollner (2017) show with Monte Carlo simulation that vivid solar-horizon twilight colors need aerosol while the purest antisolar colors occur in a purely molecular atmosphere. On the other side, paleoatmosphere work constrains composition: Catling & Zahnle (2020) for the Archean (O₂ below 10^{−6} of present, CO₂ 10–2,500 × modern, CH₄ 10²–10⁴ × modern), and Arney et al. (2016), Mak et al. (2023) and Goldblatt et al. (2024) for the organic-haze episodes. Arney's "Pale Orange Dot" computes what a hazy Archean Earth looks like from space, as an exoplanet spectrum, and Sanromá & Pallé (2012) Earth's light curves over the last 500 million years; that is as close as the literature comes. Nobody has computed the view from the ground, or the horizon-versus-zenith, latitude, and sunset structure.

The same holds for the rest of the view. Its pieces are separate results: the Moon's recession and the day's lengthening (Farhat et al. 2022), the young Sun's brightness and activity, the stars' past motions, the giant planets' early instability. Earth's transmission spectrum has been computed through geological time as a transiting exoplanet would show it (Kaltenegger, Lin & Madden 2020), and today's lunar eclipse has been modeled with refraction (García Muñoz et al. 2012), but no reconstruction of how the eclipsed Moon itself looked in past epochs turns up, nor of how these pieces together looked from the ground on a given evening. We assemble them here.

2 How the view is reconstructed

2.1 The sky's colors

For each epoch the atmosphere is built from components with their own vertical profile and spectral optical depth: Rayleigh-scattering gas (N₂, O₂, CO₂, CH₄, H₂O in their epoch-appropriate partial pressures), ozone (the Chappuis cross section of Serdyuchenko et al. 2014 at 223 K, on a layer whose peak falls from 26 km at the equator to 18 km at the pole), tropospheric aerosol, a stratospheric sulfate layer, a tholin-like fractal organic haze (strongly blue-absorbing, forward-scattering), and impact soot (Table 2). Sky radiance is integrated numerically along each line of sight through a spherical-shell atmosphere, so grazing sunlight at twilight is handled properly. The light scattered more than once is carried by a table over altitude and the Sun's local elevation, as in Hillaire (2020): from each of its nodes, rays in 576 directions gather the light scattered once on its way there and the sunlight off the ground; every later order is then solved exactly, as a

linear system for each wavelength, with the ground lit by the scattered light too, and the first four orders keep their directions, which the forward-scattering hazes and aerosols need. Against CalcMySky (Kabatsayev 2025), an independent multiple-scattering code after Bruneton & Neyret (2008) that Stellarium uses (Zotti & Wolf 2023), run on the same atmospheres, the modern sky agrees within 3% at the zenith from noon until the Sun is 20° below the horizon and within 0.002 in chromaticity, the hazy Archean and impact skies within 10% by day and 18% in twilight, and the 30-bar Hadean within 10% at the zenith wherever CalcMySky itself converges (650–750 nm), though its horizon is up to 22% brighter there (Appendix B). Spectra from 380–780 nm are converted to CIE XYZ with the analytic color-matching functions of Wyman, Sloan & Shirley (2013) and shown as sRGB. The model reproduces measured modern values (clear zenith 10,000–20,000 K, horizon 6,000–8,500 K, setting Sun ~1,700 K, pink-lavender antisolar Belt of Venus) before being pointed backward.

We treat the young Sun as a blackbody whose effective temperature and luminosity follow the solar track of Baraffe et al. (2015): 5,530 K and 68% of today's output at 4.5 Ga, rising through 5,620 K (75%) at 3.8 Ga, 5,660 K (80%) at 2.7 Ga and 5,700 K (85%) at 2.2 Ga to 5,772 K today, and 4,614 K (47%) for the 17-million-year-old Sun of 4.55 Ga; between the epochs the temperature runs linearly in time and the inverse of the luminosity too, the form of the brightening that Gough (1981) gives. The color effect is small: the 5,530 K Sun of 4.5 Ga is only about 240 K cooler in color temperature than the modern one, a difference that is barely perceptible side by side and is swamped by atmospheric effects ten to a hundred times larger. The brightness effect is not small, and is why the early-epoch skies are rendered dimmer. We ignore Fraunhofer lines and the young Sun's ultraviolet excess, which matter for haze photochemistry but not for visible color. The model is provided as the Python source `skymodel.py`; `run_epochs.py` produces the sky colors and `limb_grid.py` the limb and disk colors.

2.2 Between the epochs

The epochs are fixed points rather than the only times the view can show. The site's timeline runs from the Solar System's birth to 250,000 years ahead, and each epoch is exact at its own year, while between the epochs every quantity runs along a curve suited to it. The air (`airtime.py`) is an epoch's own at that epoch's year. Between epochs its gases run log-linearly in time from one to the next, since drawdowns and rises run roughly exponentially, with the steps the geological record shows added as fixed points of their own: the Great Oxidation Event's rise of O₂ and fall of CH₄ between 2.43 Ga (Gumsley et al.

Table 2: Atmospheres used for each epoch. Gas amounts are partial pressures in bar; AOD is tropospheric aerosol optical depth at 550 nm; haze, sulfate and soot are column optical depths at 550 nm; T_{eff} and $L/L_{\odot}$ are the assumed solar effective temperature and luminosity relative to today. The Late Cretaceous, the supernova epochs, 1900 and 2100 have today's clean air; the site draws the air of their year, which differs from today's by at most a tenth more aerosol at 66 Ma and a Sun half a percent fainter. The haze episodes keep the 2.7 Ga Sun of the clear Neoproterozoic, a percent or two fainter than the Sun of their own years in Table 1.

Epoch	Gas (bar)	O ₃ (DU)	AOD	Haze	Sulfate	Soot	T_{eff} (K)	$L/L_{\odot}$
4.55 Ga proto-Earth	CO ₂ 3, N ₂ 1, H ₂ O 0.05 (+dust 0.05)	0	0.15	–	–	–	4614	0.47
4.5 Ga Hadean	CO ₂ 30, N ₂ 1, H ₂ O 0.3	0	0.30	–	–	–	5532	0.68
4.0 Ga Hadean	CO ₂ 0.5, N ₂ 1, H ₂ O 0.02	0	0.15	–	–	–	5600	0.72
3.8 Ga Archean	N ₂ 0.8, CO ₂ 0.1, CH ₄ 0.001	0	0.08	–	–	–	5620	0.75
2.7 Ga clear Neoproterozoic	N ₂ 0.8, CO ₂ 0.05, CH ₄ 0.003	0	0.08	–	–	–	5660	0.8
2.58 Ga thin haze	N ₂ 0.8, CO ₂ 0.05, CH ₄ 0.01	0	0.08	0.15	–	–	5660	0.8
2.52 Ga thick haze	N ₂ 0.8, CO ₂ 0.05, CH ₄ 0.005	0	0.08	0.6	–	–	5660	0.8
2.52 Ga very thick haze	N ₂ 0.8, CO ₂ 0.05, CH ₄ 0.01	0	0.08	1.5	–	–	5660	0.8
2.2 Ga post-GOE	N ₂ 0.8, O ₂ 0.002, CO ₂ 0.02	66	0.10	–	–	–	5700	0.85
700 Ma Snowball	N ₂ 0.78, O ₂ 0.02, CO ₂ 0.01 (+dust 0.05)	169	0.02	–	–	–	5750	0.94
650 Ma Cryogenian	N ₂ 0.78, O ₂ 0.02, CO ₂ 0.01	169	0.10	–	–	–	5753	0.946
466 Ma Ordovician	N ₂ 0.78, O ₂ 0.17, Ar 0.01, CO ₂ 0.0025 (+dust 0.01)	291	0.10	–	–	–	5760	0.962
300 Ma Carboniferous	N ₂ 0.78, O ₂ 0.33, Ar 0.01	323	0.15	–	–	–	5765	0.975
66 Ma impact winter	modern air	300	0.15	–	0.5	1.5	5772	0.995
1816 volcanic year	modern air	300	0.10	–	0.4	–	5772	1
1980–2000 ozone-hole spring	modern air	130	0.10	–	–	–	5772	1
Modern, clean	N ₂ 0.78, O ₂ 0.21, Ar 0.01	300	0.10	–	–	–	5772	1
Modern, polluted	modern air	300	0.60	–	–	–	5772	1

2017) and 2.22 Ga (Poulton et al. 2021), O₂ held near 1% of today's through the mid-Proterozoic until the Neoproterozoic rise from about 800 Ma (Lyons, Reinhard & Planavsky 2014), and the Cambrian's 5–10% O₂ (Mills et al. 2023). Ozone is not interpolated on its own but follows the O₂, by the global-mean columns Cooke et al. (2022) simulate at fixed oxygen levels (18 DU at 0.1% of today's, 66 at 1%, 136 at 5%, 169 at 10%, 279 at today's), scaled at each epoch to that epoch's own columns by latitude. The tropospheric aerosol's optical depth runs log-linearly between the epochs, the Sun as above, the meteoric dust of the Ordovician break-up with the dust's own rise and decay (*Dust, comets and the Ordovician ring*), and the Moon-forming impact, about 4.51 Ga, is a step: the proto-Earth's air before it and the early Hadean's from it on. Figure 2 shows the result.

Some epochs are events that interrupt a longer-lived sky, and the timeline gives them dates and durations. The Neoproterozoic's haze episodes interrupt a clear background, which isotope records from South Africa and Western Australia keep returning to (Zerkle et al. 2012; Izon et al. 2015). Three episodes are recorded in the 2.65–2.5 Ga Ghaap Group alone (Zerkle et al. 2012); we date them about 2.63, 2.58 and 2.52 Ga by spacing the drill core's ends evenly, so to within tens of millions of years. The youngest, which Izon et al. (2017) resolved, set in over 0.3 Myr and lasted 1.4 Myr in all, and each episode is given that shape: the two older are the thin haze and the youngest the thick. Snowball Earth is two glaciations over a non-glacial Cryogenian: the Sturtian from about 717 Ma (MacLennan et al. 2018) to 660.98 Ma (Rooney et al. 2020), and the Marinoan, about four million years long (Tasistro-Hart et al. 2025), ending at 635.21 Ma (Prave et al. 2016). Once the ice passed a critical latitude it reached the equator within years to decades (Eberhard et al. 2023), and it melted in about two thousand years (Hoffman et al. 2017). The K–Pg impact winter lets almost no sunlight through for over a year, and its soot has cleared about five years after the impact (Bardeen et al. 2017): the site holds it for a year and clears it with a one-year e-folding time, so its sky shows for about two years over a Late Cretaceous of today's air. Tambora's sulfate veil spreads through the stratosphere over the months after April 1815, stays through 1816 and clears in 1817, and the ozone-hole sky holds from 1980 to 2000. Three more volcanic veils come over the modern-era skies as events without epochs of their own, each Tambora's air at its own veil's depth: Laki's sulfur haze from June 1783, over the Northern Hemisphere only and at Tambora's depth, though most of it lay in the troposphere (Thordarson & Self 2003), and Krakatoa's of 1883 and Pinatubo's of 1991, about 0.14 and 0.15 at 550 nm at their peaks (Sato et al. 1993), each fading with an e-folding time of about a year. As an event comes on, its own parts of the air (the haze and methane, the snowball's ice and clean air, the soot and sulfate, the ozone column) go from the background's to its own, while the rest stays the background's.

The sky's colors cannot simply be blended between epochs as differ-

ent as these, so the parts of the sky that are computed ahead of time (the day-cycle colors, the setting Sun's bands, the crepuscular rays' tables, the light in the Earth's shadow and the spectra) are computed for 143 airs along the timeline (*airgrid.py*). They are every epoch's own, the years where the curves bend, and more wherever blending the two neighbors would miss the air between them, at any of a set of test directions and Sun heights, by more than 0.02 in log₁₀ luminance (about 5%) or 0.002 in chromaticity, found by halving each interval in turn. Each event is computed at steps of its strength in the same way. The site blends the two airs either side of the time shown, luminance in logarithm and chromaticity linearly, by the year or by the event's strength. The 62 background airs lie densest where the air changes fastest: through the Hadean's CO₂ drawdown, the Great Oxidation and the Ordovician dust. The starlight's extinction, the soot's absorption, the airglow and the cloud cover follow the same blended air, and everything else follows the year too: the Sun's brightness and spots, the Moon's distance, orbit and face and the day's length, the planets' moons and rings, the stars, the Sun's place in the Galaxy, the rates of comets, meteors and dust, and the glow of cities, as the sections that follow describe.

2.3 The rest of the view

The sky's colors come from the radiative-transfer model described above; the rest of the view is drawn on them by the interactive site, in two views: a dome, the whole sky as a fisheye, and a first-person view in WebGL, with a walkable ground and clouds. Both draw on one photometric scale, calibrated in absolute units: the clear zenith with the Sun 45° up is 2.7 kcd/m², which puts the full-Moon sky at the measured 18 mag/arcsec². Stars, planets, meteors and satellites are placed by their magnitudes on that scale and dimmed by the air, 1.086 magnitudes per airmass for each unit of its optical depth at 550 nm, about 0.15 of it from the gas and the rest from the aerosol, haze, sulfate and soot; each shows only when it is brighter than the naked-eye limit for the sky around it. The Moon, moonlight, supernovae, fireballs and city glow light the sky through the same model. The clock runs over one solar day of the time shown, and the Sun follows the seasons for the date, with today's 23.4° tilt at each epoch's own year and the long-term precession around it, since the Moon has held the obliquity between about 22° and 24.5°. The Sun and Moon are drawn at four times their angular size so that their disks show on a screen, and zooming in acts as a telescope, down to a field of 14 arcseconds. Where each body was is carried back as far as it can be known, for any year. The Moon's distance follows the tidal record, the Sun's brightness and size its evolutionary track, and the stars their measured motions over the last two million years; beyond that the star field, and the planets' positions more than 10,000 years from today, are drawn at random with the right statistics, since no calculation can recover them. The colors are shown as a daylight-balanced camera would record

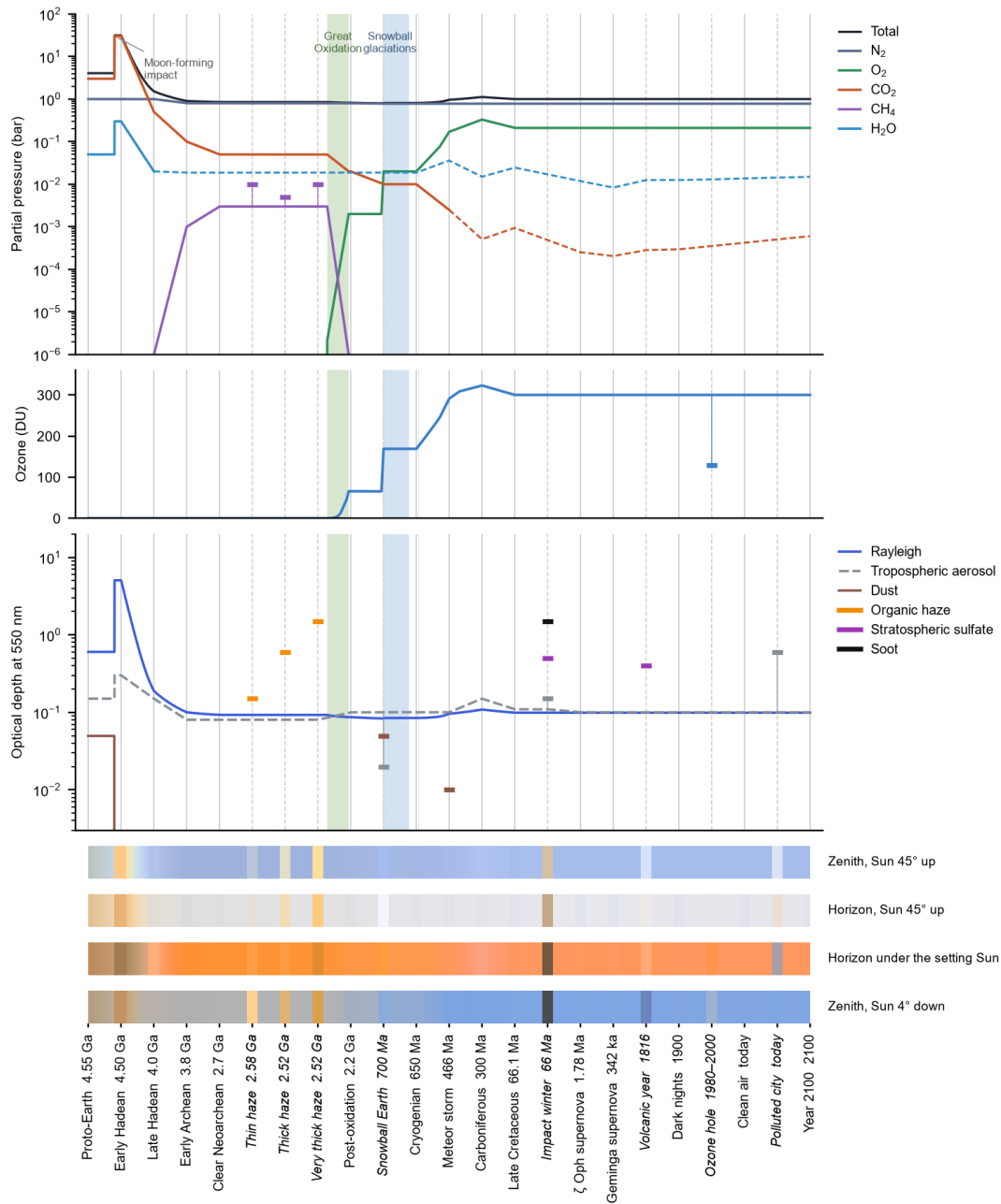


Figure 2: The air through Earth's history as the site draws it, with the epochs evenly spaced and time running linearly between neighboring epochs. Top: the gases' partial pressures and their total. Middle: the mid-latitude ozone column. Below: the optical depths at 550 nm of Rayleigh scattering and of each kind of particle. The lines are the background air through time; the air of an event (italic labels: the haze episodes, Snowball Earth, the impact winter, the volcanic year and the ozone hole) and of the polluted city is drawn as a short bar at its tick, joined to the line, as its years or million years would not show at this scale. Dashed: CO₂ after the Ordovician and water vapor after the Hadean, which the sky model leaves out once they no longer touch the visible sky. CO₂ follows the stage medians of the PhanDA reconstruction (Judd et al. 2024), about 460 ppm at 300 Ma and 940 ppm at 66 Ma; the EPICA Dome C record at 342 ka, about 205 ppm (Bereiter et al. 2015); Law Dome for 1816 and 1900, 284 and 296 ppm (MacFarling Meure et al. 2006); the measured 354 ppm of 1990 and 425 ppm of today; and 603 ppm in 2100 on SSP2-4.5 (Meinshausen et al. 2020). Water vapor is the near-surface pressure at a fixed 80% relative humidity (Held & Soden 2006) and each epoch's global mean temperature: 20 °C through the Precambrian between glaciations, the middle of the 8–30 °C the carbon cycle allows (Charnay et al. 2017; Krissansen-Totton et al. 2018); PhanDA's 31 °C at 466 Ma, 16.5 °C at 300 Ma, 24.5 °C at 66 Ma and 12.8 °C at 1.78 Ma; a glacial maximum at 342 ka, 6.1 °C under the preindustrial (Tierney et al. 2020); 13.7 °C in 1850–1900 (Jones et al. 1999), 1.4 °C more today (Forster et al. 2025) and 2.7 °C more in 2100 on SSP2-4.5 (IPCC 2021). It runs from 0.008 bar in the glacial Pleistocene to 0.036 bar in the hot Ordovician. Shaded: the Great Oxidation Event and the two Snowball glaciations. The strips are the sky's color at mid-latitude, at the brightness relative to today's clean sky used throughout: the zenith and the horizon with the Sun 45° up, the horizon under the setting Sun, and the zenith with the Sun 4° below the horizon, from the airs the site blends between the ticks and each epoch's own at its tick (*air_timeline_fig.py*).

them, without chromatic adaptation, and the night as a dark-adapted eye sees it. The scenery and the clouds are drawn, not modeled; the sky is the model.

2.4 The ground

The ground is scenery, like the clouds: a walkable landscape chosen for each era rather than computed, lit by the model's sky and Sun. The proto-Earth has magma pools; the 4.5 Ga Earth a hot ocean, cooling as the CO₂ was drawn down (about 230 °C while 100 to 200 bars remained; [Zahnle et al. 2010](#)), steaming round volcanic islands; the Archean, water and volcanic shields; Snowball Earth, ice plateaus with blue banded cliffs and frozen ponds, open water again in the Cryogenian between the glaciations; the Ordovician, shallow seas with no land plants beyond mosses and crusts; the Carboniferous, forest and swamps; the Late Cretaceous, forest, dead woods in its impact winter; the Pleistocene, 1816 and 1900, woods and snow-capped peaks; and the modern epochs, a town with lit windows. The ground's color, the snow on the peaks, the Snowball's snow cover and its ice halos cross-fade with the year and with an event's strength, while the layout of the scenery changes with the epoch. Water reflects the sky and glitters in the Sun and Moon, and below the glare it has the epoch's own color, which cross-fades too. The Hadean is clear, as dissolved ferrous iron barely colors water. The Archean's is green: Fe(III) hydroxide, from iron oxidized by ultraviolet light and by early photosynthesis, absorbs the blue and water the red, so the light under water was mostly green ([Matsuo et al. 2025](#)), more so by the Neoproterozoic. After the Great Oxidation Event the iron settles deeper and the shallows are olive and teal, with purple slicks of sulfur bacteria where sulfide reached the sunlit water, as it did in restricted basins and lakes ([Brocks et al. 2005](#); [French et al. 2015](#)). Rock flour from the glaciers clouds the Cryogenian's lakes turquoise; with no land plants to stain it brown, the Ordovician's water is a clear blue; from the Cretaceous on it is today's, gray with ash in the impact winter and green with algae in a polluted city. These colors are chosen from the chemistry, not computed. Lava glows; distant scenery fades into the sky's color. None of this is part of the model: the sky above it is.

3 The sky by day and at dusk

3.1 Horizon versus zenith

In a clean molecular atmosphere the zenith is blue and the horizon white because the horizon path is long enough that blue is scattered back out before reaching the eye and multiple scattering fills in the other colors. The size of that gradient is the clearest single diagnostic of atmospheric state. It is largest in the cleanest atmospheres (Snowball Earth, today's clean air: 6,800–11,500 K of color-temperature difference at mid-latitudes and the poles), shrinks as Rayleigh depth rises (late Hadean), collapses to nothing when a broadband absorber or thick scatterer sits overhead (hazy Archean, impact winter, 30-bar Hadean), and falls to a third or less under a stratospheric sulfate veil or heavy pollution, which whiten the zenith toward the horizon's color.

3.2 Equator, mid-latitudes, poles

Latitude enters through solar elevation and surface albedo. A high Sun lights the sky from above through a short path, giving a brighter but paler zenith (equatorial noon ~8,300 K); a low Sun sends light through more air, so the polar summer zenith is a deeper, darker blue (~17,800 K today, 16,800 K over Snowball ice) while the polar horizon is warmer and yellower. The same geometry makes the poles the place where any overhead absorber is most visible: the hazy Archean sky is cream at the equator but distinctly orange-yellow at the poles, and the impact-winter Sun that is still a pale disk at the equator is gone at 75° latitude. Snow and ice brighten the dome and deepen the zenith's blue by reflecting light back into the atmosphere, though polar and Snowball horizons still whiten as a land horizon does.

3.3 Particulates

Three kinds of particle appear in the record, and each leaves a different sky. Non-absorbing sulfate high in the stratosphere (volcanic years) whitens the day sky and produces long, luminous pink and lavender twilights, because the layer is still sunlit after the ground is dark. Absorbing organic haze (Neoproterozoic) or soot (impact winter) removes blue outright, turning the dome tan or amber with almost no directional structure, and dims the surface by factors of 3–20. Boundary-layer pollution or dust brightens and grays the zenith, and buries the setting Sun in murk before it reaches the horizon. Tropospheric aerosol is also what makes sunset color vivid: the model confirms the result of [Lee & Mollner \(2017\)](#) that a purely molecular sky yields a pale, yellow-orange horizon while any turbidity deepens it to red.

3.4 Sunsets and sunrises through time

The biggest surprise is ozone. Today the sky above a setting Sun grades from orange through pale yellow to a zenith that stays blue well into twilight: about 24,000 K with the Sun 4° down. That persistent blue is the Chappuis band, ozone absorbing yellow and orange along the grazing path. The same modern sky with the ozone removed drops that zenith to a neutral gray, about 6,700 K. Before the Great Oxidation Event there was no ozone, so every sunset for the first two billion years ended with the zenith fading to gray. At ~2.2 Ga a 66 DU column, the [Cooke et al. \(2022\)](#) global mean for 1% of present oxygen, turns that gray zenith a pale blue near 8,400 K. The deep twilight blue arrives later, once the column is near modern: the snowball sky, at their 10% oxygen column of 169 DU, holds a dusk zenith near 16,000 K. The same thinning is visible in the ozone-hole years. A polar-spring column of 130 DU leaves the dusk zenith pale blue, near 9,900 K, against 24,000 K today. Beyond the ozone story: Hadean sunsets were not events at the horizon but a slow dimming of the whole glowing dome; hazy Archean sunsets were the longest and most saturated in Earth's history, vermilion at the horizon and amber overhead; Snowball sunsets were brief and golden; the sunsets of the impact winter did not exist as color at all; and the reddest, most theatrical skies of the Phanerozoic belong to volcanic years like 1815 and 1883.

3.5 The atmosphere from space

To show latitude and altitude at once, these renderings look at Earth from space with the Sun behind the viewer at the equinox, so the solar zenith angle at every point equals its latitude (equator at the center line, poles at top and bottom). The shell around the disk is the atmosphere's limb: the color of light scattered toward the viewer along a tangent ray at each altitude, computed with the same model. The atmosphere is drawn 30 times too thick, so 100 km spans half an Earth radius; a real limb is a hairline. The disk shows the planet's reflected color over a dark ocean (over ice for Snowball Earth), with limb brightness compressed so faint upper layers remain visible.

Modern, clean air. Modern Earth for reference: white-blue troposphere grading to a deep blue stratosphere and fading to black, brightest at the equator and darker toward the poles.

Early Archean, ~3.8 Ga. Clear early Archean. Structurally modern: white-blue near the surface, deep blue above, fading to black. With a little more CO₂ and no ozone the shell is marginally paler than today's and the disk very slightly whiter.

Neoproterozoic haze episode, ~2.52 Ga (thick haze). Hazy Neoproterozoic. The organic haze colors the entire limb tan: every tangent ray below ~60 km crosses the layer (centered ~45 km) twice. Only above it does the shell turn a faint, dusty blue. The disk is the pale orange dot, though from space it is a subtle cream-orange rather than a vivid one.

Early Hadean, ~4.5 Ga. 30-bar CO₂ Hadean. The shell is an opaque, luminous white-peach almost all the way up, because tangent rays at any tangent height below ~60 km pass through many optical depths of CO₂; only the outermost fringe thins to blue. The disk is bright and nearly white: a cloudless, Rayleigh-only Venus.

Snowball Earth, ~700 Ma. Snowball Earth. The bluest shell in the set above a blazing white disk of ice. The polar limb stays bright because the frozen surface reflects so much light back into the atmosphere.

Carboniferous, ~300 Ma. Carboniferous, 33% O₂. The extra oxygen raises total pressure by about a tenth, so the limb is marginally thicker and brighter than today's, but to the eye it is indistinguishable from modern Earth: once ozone and clean air are in

Table 3: Summary of sky colors by epoch (mid-latitude noon unless stated).

Epoch	Noon zenith, mid-latitude	Horizon	Sunset
4.55 Ga, proto-Earth	Pale blue-white under 3 bar of CO ₂ and dust	Milky	Orange; a Sun larger and redder than today's
4.5 Ga, 30-bar CO ₂	Peach-white, 3,500 K, shadowless	Same as zenith	Whole dome dims to orange; Sun rarely visible
4.0 Ga, 0.5-bar CO ₂	Pale milky blue, 10,900 K	Milk white	Deep red Sun; gray twilight (no ozone)
3.8 Ga, clear Archean	Blue, 12,700 K	White	Modern-like, then a gray twilight zenith
2.7 Ga, clear Neoproterozoic	Blue, 12,700 K	White, 6,600 K	Modern-like, then a gray twilight zenith (~6,600 K)
2.58 Ga, thin haze	Pastel milk-blue, 8,200 K	Warm white, 5,900 K	Orange twilight all the way to the zenith
2.52 Ga, thick haze	Cream-tan, 5,600 K	Cream-tan	Vermilion horizon, amber sky, long orange dusk
2.52 Ga, very thick haze (upper bound)	Saturated apricot, 4,100 K	Same as zenith	Sun lost in the haze before it sets; orange dusk
2.2 Ga, post-GOE	Blue, 12,200 K	White	Pale blue twilight zenith (~8,400 K); deep blue dusk comes later
700 Ma, Snowball	Deep blue, 15,400 K	White, 7,000 K	Golden, pale
650 Ma, Cryogenian	Blue, 12,700 K	White, 6,800 K	Orange; blue dusk zenith (~13,300 K)
466 Ma, meteor storm	Blue, 12,900 K	White, 6,800 K	Modern-like; at night a hundred times today's fireballs and a bright zodiacal band
300 Ma, 33% O ₂	Blue, 12,300 K	White, slightly brighter	Modern-like; smoky more often
66.1 Ma, Late Cretaceous	Same blue as today	White	Modern
66 Ma, impact winter	Dim amber-beige, 4,800 K	Beige	None; dome fades to brown
1.78 Ma, ζ Oph supernova	Same blue as today	White	Modern; a magnitude −11.6 supernova low in the south
342 ka, Geminga supernova	Same blue as today	White	Modern; a magnitude −11 supernova in Orion that casts shadows
1816, volcanic year	Milky blue-white, 8,600 K	White, 6,300 K	Salmon Sun, pink-lavender afterglow
1900, dark nights	Same blue as today	White	Modern; no city glow after dark
1980–2000, ozone-hole spring	Blue, still	White	Pale blue dusk zenith, ~9,900 K
Today, clean	Blue, 13,800 K	White, 7,000 K	Orange horizon, pink-lavender antisolar; twilight zenith ~24,000 K
Today, polluted city	Pale gray-blue, 7,700 K	Warm white, 5,800 K	Sun lost in gray murk before the horizon
2100, megaconstellation	Same blue as today	White	Some 1,600 datacenters brighter than fifth magnitude along the dusk terminator, plus a few hundred communications satellites

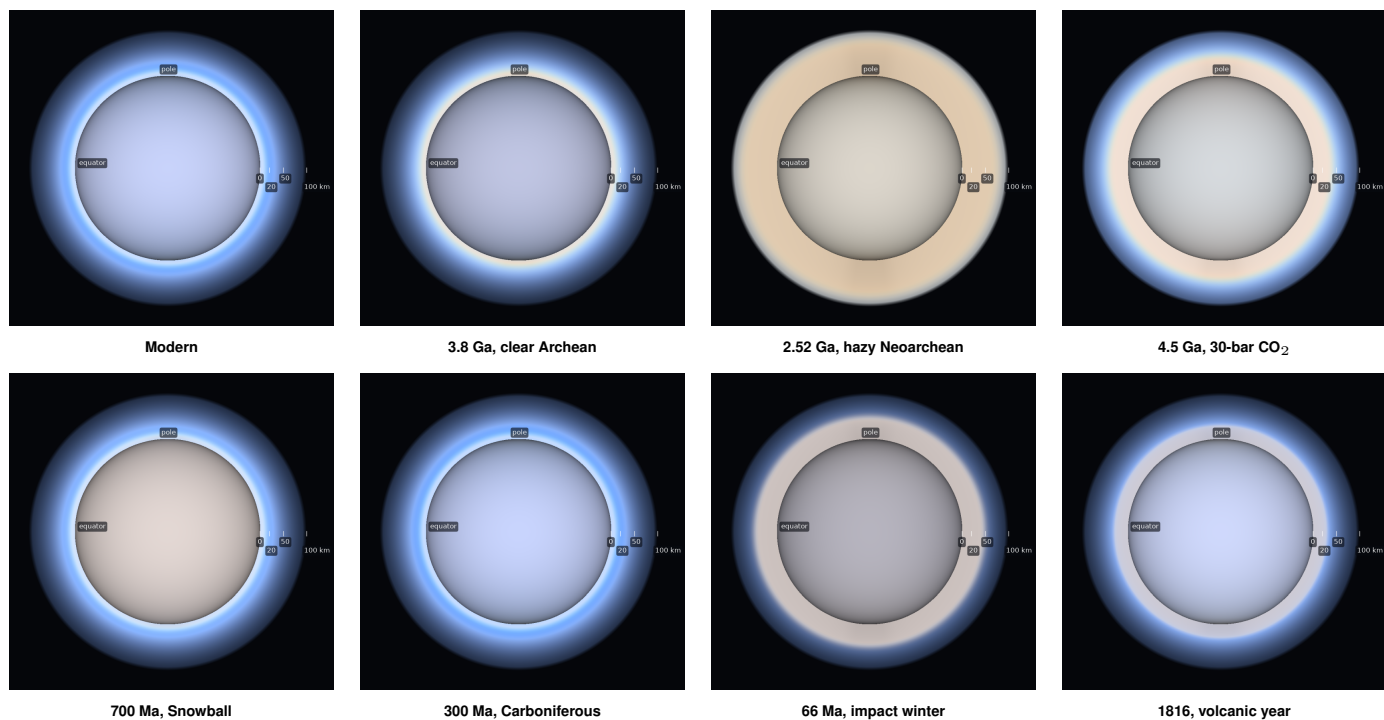


Figure 3: Volumetric renderings of the atmosphere at eight epochs. Equinox geometry with the Sun behind the viewer; the shell is the limb color along tangent rays, drawn 30 times too thick (100 km spans half an Earth radius); the disk is the planet's reflected color over ocean (ice for Snowball Earth). Limb brightness is compressed so faint upper layers remain visible.

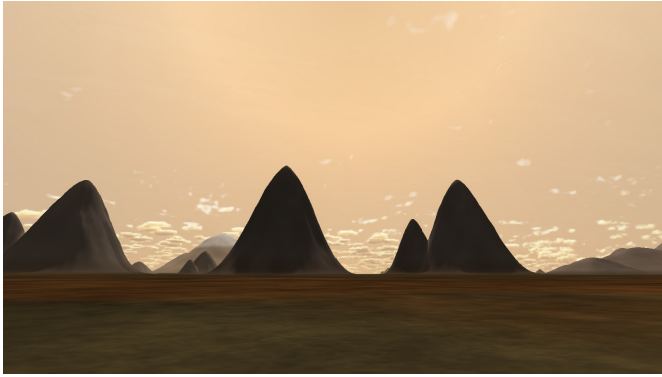


Figure 4: Noon months after the Chicxulub impact, at 66 Ma: soot and sulfate turn the sky a dim, uniform amber-beige with no blue at all, about a fifth as bright as a clear sky, with almost no cloud.



Figure 5: An afternoon at 2.52 Ga under the thick organic haze, as the site's first-person view draws it: a pale orange dome with almost no difference between zenith and horizon, the Sun a soft glow behind broken cumulus lit gold by its haze-reddened light.

place, the sky from space has been the same pale blue dot for two billion years.

K-Pg impact winter, 66 Ma. Impact winter. A dim brown-gray band from the soot and sulfate layer occupies the lower and middle shell; above ~ 40 km the untouched upper atmosphere is still faintly blue. The disk is a dull gray-lilac, and dark at high latitudes.

Volcanic year, 1816 (Tambora). Volcanic year. A milky white sulfate band near 20 km sits between the white-blue troposphere and the deep blue upper shell. The disk is brighter and whiter than clean modern Earth.

3.6 Clouds

Clouds are not part of the radiative-transfer model; the first-person view draws them as scenery, ray-marched through a volume and lit by the model's sky, the Sun and the Moon, and by a supernova, a fireball or city light when there is one. Their regimes are illustrative choices for each era rather than results: a near-overcast stratiform deck under the steamy Hadean CO_2 (88% cover at 4.5 Ga), scattered cumulus in the Archean thinning as the haze thickens (from 48% at 3.8 Ga to 16% under the thickest haze), sparse thin cloud over the frozen Snowball (22%), towering convection in the warm Carboniferous (82%), almost none in the impact winter (8%), and more cirrus in the volcanic year. Between the epochs the regime runs from one epoch's to the next's with the year, and toward an event's own with its strength. The weather changes over days and the clouds through each day: cumulus days build to an afternoon peak and stratiform ones burn off by midday. The kind of cloud changes from day to day as well as the amount: ahead of a front the cloud spreads into sheets and the cirrus thickens, behind it the cold air builds cumulus, an unstable day grows taller towers than a stable one, and the base sits lower on a damp day than a dry one, each about the era's own regime. Each date has its own clouds, and the noise they are drawn from is read on a slanted slice so its 9 km tile does not repeat across the sky. After sunset the clouds stay lit from below until the Earth's shadow climbs past them.

3.7 Crepuscular rays

Where the Sun shines from behind a cloud, beams fan out across the sky and the sky between them darkens: crepuscular rays, the cloud's

shadow in the sunlit air. Only the part of each direction's light that is sunlight scattered once in the lower air can be shadowed, so the page computes that share from each air along the timeline, its gas, aerosol, dust, haze, sulfate and soot layers with their heights, for every Sun height and direction (*shafts.py*); along each line of sight the stretches whose path to the Sun passes through cloud lose their share. The rays are strongest where the scattering sits low, and weakest in the 30-bar Hadean, whose light is multiply scattered and comes from everywhere at once. The Moon makes the same rays through gaps in cloud, and so does a bright fireball.

3.8 Rainbows

Rain falls from the clouds drawn above it, from the same day-to-day weather: steady rain under the thicker parts of a deck when a front comes, showers under the tallest cells on an unstable afternoon, drizzle from a low damp deck, and snow when the ground is near freezing or below. Where sunlight reaches the falling rain through gaps in the cloud, the drops scatter it as water spheres do, so a shower with the Sun behind the eye shows its rainbows: the primary 42° from the point opposite the Sun, red on the outside, with the sky inside it brighter; Alexander's dark band beyond it; and the fainter secondary at 51° , its colors reversed. The drops' scattering is worked out by geometric optics for each number of reflections inside the drop, with the Fresnel share of each polarization, and by Airy theory about the primary and secondary bows (Airy 1838), which sets their widths and the supernumerary bands inside them. It is spread over a range of drop sizes and blurred by the Sun's disk, and colored through the solar spectrum; against Lorenz–Mie theory for drops of 0.1 and 0.3 mm the primary's peak falls within 0.05° and its height within 4%, while the secondary comes out 15–30% faint. The drop size comes from what is falling: steady rain and showers by the Marshall–Palmer median drop (Marshall & Palmer 1948), up to 1 mm, past which drops flatten and their bows break up; drizzle, of 0.15 mm, gives a broad, pale bow. Snow makes none.

The bows move with the epoch, because their radii depend on how much more strongly water bends light than the air around it. Water's refractive index is taken at the rain's temperature (Harvey et al. 1998), and the air's from each epoch's gases at their pressures. Hot water bends light less, and so does dense air. In the Early Hadean, under 30 bars of CO_2 with rain near 85°C , the primary widens to 45.6° and the secondary narrows to 44.6° , so the two cross and the dark band between them is gone. In the proto-Earth's guessed 4 bars at 90°C the band narrows from today's 9.7° to 3.7° , and in the Late Hadean the primary sits at 42.2° . In every later epoch the bows lie within 0.3° of today's 41.8° and 51.5° . The Hadean's bows would rarely be seen: in that heat nearly all the rain evaporates before it lands, and little direct sunlight gets through the air. The bow's brightness rests on how much sunlight the drawn clouds let under them, so it is an estimate; the Moon's faint bow is not drawn.

3.9 Fog, fogbows and glories

Cloud and fog droplets, a few to twenty microns across, scatter light in ways geometric optics misses. Their bows are broad and nearly white, with an orange outer rim and a bluish inner one: the fogbow, some $37\text{--}39^\circ$ from the antisolar point, a little inside the rainbow's 42° . Straight back toward the Sun they send a glory, colored rings of a degree or two around the antisolar point, a wave effect of light grazing the droplets' edges. Both are worked out by Lorenz–Mie theory, over a gamma distribution of droplet radii (Hansen & Travis 1974) of effective variance 0.1 for clouds and 0.15 for fog, through the solar spectrum and blurred by the Sun's disk. The smaller the droplets, the whiter and narrower the bow and the larger and brighter the glory (Lynch & Schwartz 1991; Gedzelman 2003). Glories are brightest for droplets of 10–20 microns (Lock 1989), and their sharp rings show how narrow real droplet distributions are (Mayer et al. 2004).

The droplets' size follows how much the air offers water to condense on. Few particles make few, large droplets; many make many small

ones. Today's cloud droplets are about 10–14 microns over the oceans and 6–9 over land (Han et al. 1994). Before life the air had only sea salt and volcanic sulfate to seed clouds, so their droplets were large: 16 microns is drawn, as Archean climate studies take (Rosing et al. 2010; Wolf & Toon 2014). The Archean's organic haze takes up water (Hasenkopf et al. 2011) and seeds more droplets, 13 microns. Land plants' vapors bring them to 11 microns from the Ordovician on. The sulfate of the 1815 eruption and the Chicxulub impact's sulfate and soot make them small, 9 and 7 microns, as today's polluted air does. Fog droplets are drawn smaller than the same air's cloud droplets. These sizes are estimates. In the dense, hot air of the Early Hadean the droplets bend light less, as the raindrops do, so the bows widen by some 4° .

Single-scattered sunlight on the clouds takes the droplets' structure past 95° from the Sun, so a sunlit cloud opposite a low Sun can carry a faint cloudbow. In the Snowball's frozen air the clouds are ice and show halos instead. Radiation fog forms on still, damp, clear nights, as the ground cools the air over it to its dew point. It fills the low ground, deepest about sunrise, and burns off as the Sun climbs past 16° , thinning and sinking as it goes. Inside deep fog no sunlight gets through. In the shallow mist of its last hour a fogbow shows opposite the Sun. From a hill above the fog its top lies like a sea, with the glory around the antisolar point and the fogbow's ring around that. Fog is drawn in every epoch with land and liquid water, but not on the Hadean's hot seas, whose steam stands in for it, and not in air below -15°C , where it is ice.

3.10 Ice halos

In clear, very cold air the sky fills with diamond dust, tiny hexagonal plates and columns of ice drifting near the ground. Snowball Earth's air would have been full of them at every latitude (Figure 6). Today they are common on the Antarctic plateau and in Arctic winter, so they are drawn at 75° in the modern epochs and in the other cold epochs (2.2 Ga at the end of the Huronian glaciations, the cold Cryogenian between the snowballs, the Late Ordovician and Late Paleozoic ice ages, and the Pleistocene), and faintly at 45° at 342 ka, a glacial maximum. Between the epochs their strength runs on with the year, and the Snowball's come and go with its ice.

The halos are traced from the crystals' geometry with the refractive index of ice at 450, 550 and 650 nm (Warren & Brandt 2008), so each arc carries its own dispersion, red toward the Sun: the 22° and 46° halos, the upper and lower tangent arcs, the sun dogs (which move out with the Sun's height and vanish above 61°), the circumzenithal arc (only while the Sun is below 32°), the parhelic circle with its 120° parhelia, a sun pillar for a low Sun, and the diffraction aureole. The Moon makes the same, faintly. Their brightness, set against the clean noon sky, is an estimate of a good display; the air in front of them is each epoch's.

4 The Sun

4.1 The young Sun

The Sun was about 30% fainter when the Earth formed and has brightened since, as hydrogen burning has raised the density and temperature of its core. We follow the $1\text{ M}_\odot$ track of Baraffe et al. (2015): 68% of today's light and 5,530 K at 4.5 Ga, 80% and 5,660 K at 2.7 Ga, 94% at 700 Ma, today's 5,772 K by the Cenozoic, and between the epochs as Gough (1981) gives the brightening, the inverse of the luminosity linear in time. Its radius follows from the luminosity and temperature: 0.90 of today's at 4.5 Ga, 0.93 at 2.7 Ga, 0.98 at 700 Ma, so the young Sun's disk was smaller as well as dimmer, and the closer Moon covered it easily. The 4.55 Ga Sun is different. Seventeen million years old, it is still contracting onto the main sequence: cooler, 4,614 K, at 47% of today's light but 7% larger than today's, an orange-white disk. The color change is small, two or three hundred kelvin for most of the record, and swamped by the air's;

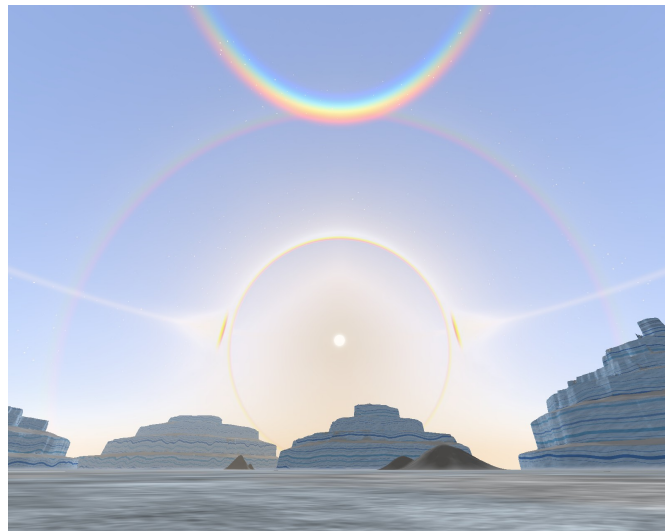


Figure 6: A morning on Snowball Earth at 700 Ma, from mid-latitudes, the Sun 22° up through clear air full of diamond dust: the 22° halo with its tangent arcs hugging its top and bottom, the sun dogs just outside it, the faint 46° halo, the circumzenithal arc high overhead, and the parhelic circle running level through the Sun. Each arc is red on its side toward the Sun.

the brightness change is not, and it is why the early skies are drawn dimmer. The Earth–Sun distance varies through the year with today's eccentricity, so the Sun is 3.4% brighter at perihelion in January.

4.2 Sunspots

The Sun's disk carries its spots and faculae, drawn from a map of the whole photosphere made for each epoch and day and turned with the Sun's rotation. How spotted the Sun was follows its age. Young solar analogs are spotted over 1 to 10% of their surface, the coverage falling roughly as the inverse square root of age (Morris 2020) and much faster once the rotation period passes about 15 days (Nichols-Fleming & Blackman 2020). Stars more active than Rossby number one, the Sun before about 2.5 Gyr, dim when they are active: dark spots dominate their variability. Older, quieter stars like today's Sun brighten with activity, dominated by bright faculae (Shapiro et al. 2014; Reinhold et al. 2019), because spot area grows faster with activity than facular area does (Nemec et al. 2022). The Sun's rotation follows the slow-rotator sequence it most likely took (Gallet & Bouvier 2013): 3.1 days at 4.5 Ga, 16 at 2.7 Ga, 23 at 700 Ma. Between the epochs the spot coverage and spot sizes run geometrically from one epoch's to the next's and the rotation smoothly, by the square of the period.

Fast rotators carry spots at high latitudes and large cool polar caps, as Doppler images of young solar analogs show (Strassmeier 2009; Barnes et al. 2005), so the Hadean and early Archean Suns have their spots between 10° and 75° and caps round the poles. A regular cycle sets in at a few hundred million years (Katsova 2020); from 2.7 Ga the spots emerge in a butterfly pattern, from mid-latitudes toward the equator over each cycle (Hathaway 2011), on cycles lengthening from 8 to 11 years. On Gregorian dates the modern epochs follow the real cycles, each cycle's sunspot number from the SILSO record with the shape of Hathaway, Wilson & Reichmann (1994): the 1816 volcanic year falls in the Dalton Minimum and dates in the Maunder Minimum are all but spotless. Beyond the record a sixth of the time is a grand minimum, as over the Holocene (Usoskin, Solanki & Kovaltsov 2007).

Each active region is a bipolar group: a large, round leading spot ahead in the rotation and nearer the equator (Joy's law), a following polarity broken into smaller spots, often with partial penumbrae, and pores between. Peak areas are lognormal (Baumann & Solanki 2005); a group grows in days and decays linearly, faster the smaller it is, and drifts with the latitude's rotation (Snodgrass 1983). The spots have the structure seen in white light (Solanki 2003; Borrero & Ichimoto 2011): an umbra of 3,700 to 4,600 K, darker the larger it is, sprinkled with

umbral dots and crossed in the larger spots by granular light bridges; a penumbra of radial filaments 150 to 650 K below the photosphere, with bright grains at their inner ends and a ragged, comb-like outer edge; and round the region, faculae that show only toward the limb, cleared from a moat round each mature spot, over the faint network of the supergranulation. Intensities are Planck ratios at the color channels' wavelengths, so spots are redder as well as darker. The disk is drawn as a white-light photograph is shown, with umbrae near-black and penumbrae mid-gray. Zoomed further, past the map's resolution of about 1,000 km, the photosphere's own fine structure takes over (*The Sun close up*).

A spot about an arcminute across, some 500 millionths of the hemisphere, is the smallest the eye can see unaided through a haze or a filter (Vaquero 2007). Today one is on the disk about one day in 25, mostly near solar maximum; at 2.2 Ga every other day; in the Archean and Hadean always, about 30 at once at 4.5 Ga. Spots then take about 3% off the Sun's light, and they gather toward the poles, darkening the top and bottom of the disk. The young Sun's shape does not change visibly: rotating in 3 days flattens it by only 0.05%, and even a 1-day rotation by 0.5%, 10 arcseconds off the width of a 32-arcminute disk.

4.3 The Sun close up

Zoomed in, down to a field of view of 14 arcseconds, the photosphere is drawn as high-resolution solar telescopes show it: granulation, convection cells about 1,300 km across, bright where hot gas rises and dark in the narrow lanes where it sinks, living about eight minutes, a fifth of the larger ones splitting from a dark knot late in life (exploding granules); magnetic bright points a couple of hundred kilometers across in the lanes inside faculae; penumbral filaments a few thousand kilometers long; umbral dots about 1,000 K hotter than the umbra around them; and toward the limb the supergranular network, cells some 30,000 km across outlined by brightenings. Spot and plage edges are ragged down to the pixel. This fine structure is the same in every epoch; only the spots and faculae change with the Sun's age (Figure 7).

In the first-person view a Sun near full daylight is not drawn as a disk at all but as the eye sees it: a blinding white blank tinted the epoch's color, in a bloom that whitens the sky around it. Zooming in, as through a filter, dims it to the real disk, and the glare eases off as the Sun sets or is eclipsed, until the corona and Bailey's beads take over.

4.4 The setting Sun

Near the horizon the Sun is drawn as twenty images, one per 20 nm band from 385 to 765 nm, each lifted by its own refraction (the dispersion of air, Edlén 1966) and dimmed by its own optical depth along the grazing path through the epoch's model atmosphere. At the horizon the green and orange images of today's Sun are only about 6 arcseconds apart, so the colors separate only in the last sliver: the green flash is whichever band survives the extinction last, and the cleaner the air the shorter that wavelength. Along the horizontal path, the model's air still passes a twentieth of its peak sunlight at 550 nm in the clean, dry Snowball epoch, the best flashes in the record, and at 630 nm in today's clean air; under the Neoproterozoic haze, the impact-winter soot, a volcanic veil or a polluted city nothing shorter than 650 to 730 nm gets through, and there is no flash at all.

How far the air lifts the Sun follows its refractivity, the sum over its gases' partial pressures. Today's horizon refraction of about 34 arcminutes is 1.8 times larger at 4.0 Ga (half a bar of CO₂ on a bar of N₂), 1.11 times in the oxygen-rich Carboniferous and 0.83 times in Snowball Earth's thinner air, so the Sun sets later or earlier by a minute or two. The 30-bar Hadean air is 47 times as refractive as today's: a horizontal ray bends faster than the ground curves and is trapped (ducting), but its Sun is lost in Rayleigh scattering long before it reaches the horizon, so we hold the drawn bending to three times today's.

Each evening also has its own layering of the low air, set by the date so that a given evening always sets the same way. Thin temperature inversions step the disk's edge, show a strip of it twice (once inverted) where the rays cross, and draw a dark line across it where trapped rays run through the densest air; over warm water the Sun meets its own inverted image in an inferior mirage, the "omega" sunset. The cold surface of Snowball Earth makes inversions common and inferior mirages rare, and the warm oceans of the Hadean and Archean the reverse. These mirage statistics are illustrative. The disk is also darker and redder toward its edge (limb darkening, Hestroffer & Magnan 1998): the air only multiplies the Sun's light, so the darkening is the same under every sky.

Two of these effects are drawn larger than life. The disk itself is drawn at four times its angular size, as the Moon is, so that it shows at all on a screen, and the bands' separation by refraction is enlarged with it, four times high in the sky and up to 24 times at the horizon, where a real flash is a sliver of a few arcseconds. And the limb darkening is drawn at a fifth of its true strength: on a disk drawn near white, the real contrast reads as a dark rim. The spectrum readout keeps the full law.

4.5 Solar eclipses

When the Moon covers part of the Sun, all the sunlit sky dims by the fraction of the disk still showing. In totality the sky is lit from beyond the Moon's shadow, tens to a hundred kilometers away, where the Sun is still partly up: the epoch's own twilight sky with a sunset glow all round the horizon, a thousandth of the day sky, as measured (Sharp, Lloyd & Silverman 1966). The Hadean and hazy Archean totality skies are therefore that era's dusk, peach or amber rather than the deep blue of a modern eclipse.

The corona follows the Sun's age. A younger Sun spun faster and was far more active: its X-ray output goes as age to the -1.5 (Güdel, Guinan & Skinner 1997), about 530 times today's at 4.5 Ga, and its coronal temperature with it, 7.7 MK against 1.5 MK. Today's corona (Baumbach 1937: electron-scattered K light near the limb, dust-scattered F light beyond about 2.3 solar radii) is scaled accordingly: a denser, more extended K corona, an F corona that follows the era's zodiacal dust, stronger coronal lines (the green Fe XIV and red Fe X, joined by yellow Ca XV in the hot young corona) and a brighter pink chromosphere. These scalings are estimates. The young Sun was also smaller (0.90 of today's radius at 4.5 Ga) while the Moon was closer, so early eclipses hide the inner corona: at 3.8 Ga the Moon looks 1.5 times the Sun's width, and from 2.2 Ga back every central eclipse is total. Through the 30-bar Hadean air, at 5.8 magnitudes of extinction per airmass, behind a Moon eight times the Sun's width, the corona hardly shows: only its outer part clears the Moon's limb, a faint glow lost in the molten Moon's own aureole. The proto-Earth of 4.55 Ga has no Moon, and so no eclipses; its Sun, 17 million years old, has the saturated corona of a star that young, at about 9 MK.

The eclipse itself is drawn from the Moon's real profile: at second and third contact the last sunlight breaks into Bailey's beads where the lunar limb's valleys, from the Laser Altimeter's heights, let the photosphere through, and a diamond ring. Like the disks, the eclipses are enlarged: the Sun and Moon are drawn at four times their size, and eclipses are found and timed with the enlarged disks, so the page's partial phases last longer, and its eclipses happen at more places, than real ones. For each new Moon the page stands where parallax brings the Moon closest to the Sun, the best seat for that eclipse.

Table 4: Sunspots by epoch, from the site's spot model. Coverage is the share of the surface in spots and their penumbrae: the mean, and the 5–95% range over the cycle or the young Sun's irregular swings. A naked-eye spot is one over about 500 millionths of the hemisphere, an arcminute across, on the visible disk; the modern row is 1996–2026 on the real cycles. Rotation is the equator's sidereal period.

Epoch	Sun's age	Rotation	Spot coverage	Spots emerge at	Cycle	Days with a naked-eye spot
4.55 Ga proto-Earth	0.017 Gyr	1.6 d	10%	25–80°; polar caps hold 45% of the spotted area	none	all
4.5 Ga Hadean	0.07 Gyr	3.1 d	9% (7–11%)	22–75°; polar caps above 72°	none	all (about 30 at once)
4.0 Ga Hadean	0.57 Gyr	9.0 d	4% (2.9–5.3%)	15–65°; caps above 81°	about 5 yr, shallow	all (about 14)
3.8 Ga Archean	0.77 Gyr	10.4 d	3% (1.9–4.3%)	10–60°; caps above 85°	about 6 yr	all (about 11)
2.7 Ga Archean	1.87 Gyr	16 d	1% (0.3–1.8%)	from 40° toward the equator	8 yr	83%
2.2 Ga post-GOE	2.37 Gyr	18 d	0.5% (0.1–1.0%)	from 34°	9 yr	50%
700 Ma Snowball	3.87 Gyr	23 d	0.25% (0.02–0.5%)	from 30°	10.5 yr	20%
466 Ma Ordovician	4.10 Gyr	24 d	0.20% (0.01–0.4%)	from 29°	10.8 yr	18%
300 Ma Carboniferous	4.27 Gyr	25 d	0.17% (0.01–0.4%)	from 28°	11 yr	12%
66 Ma impact winter	4.50 Gyr	25 d	0.14% (0.01–0.3%)	from 28°	11 yr	8%
1816, 1900, today and 2100	4.57 Gyr	25.4 d	0.09% (0.01–0.19%)	from 28°	the real cycles	4%

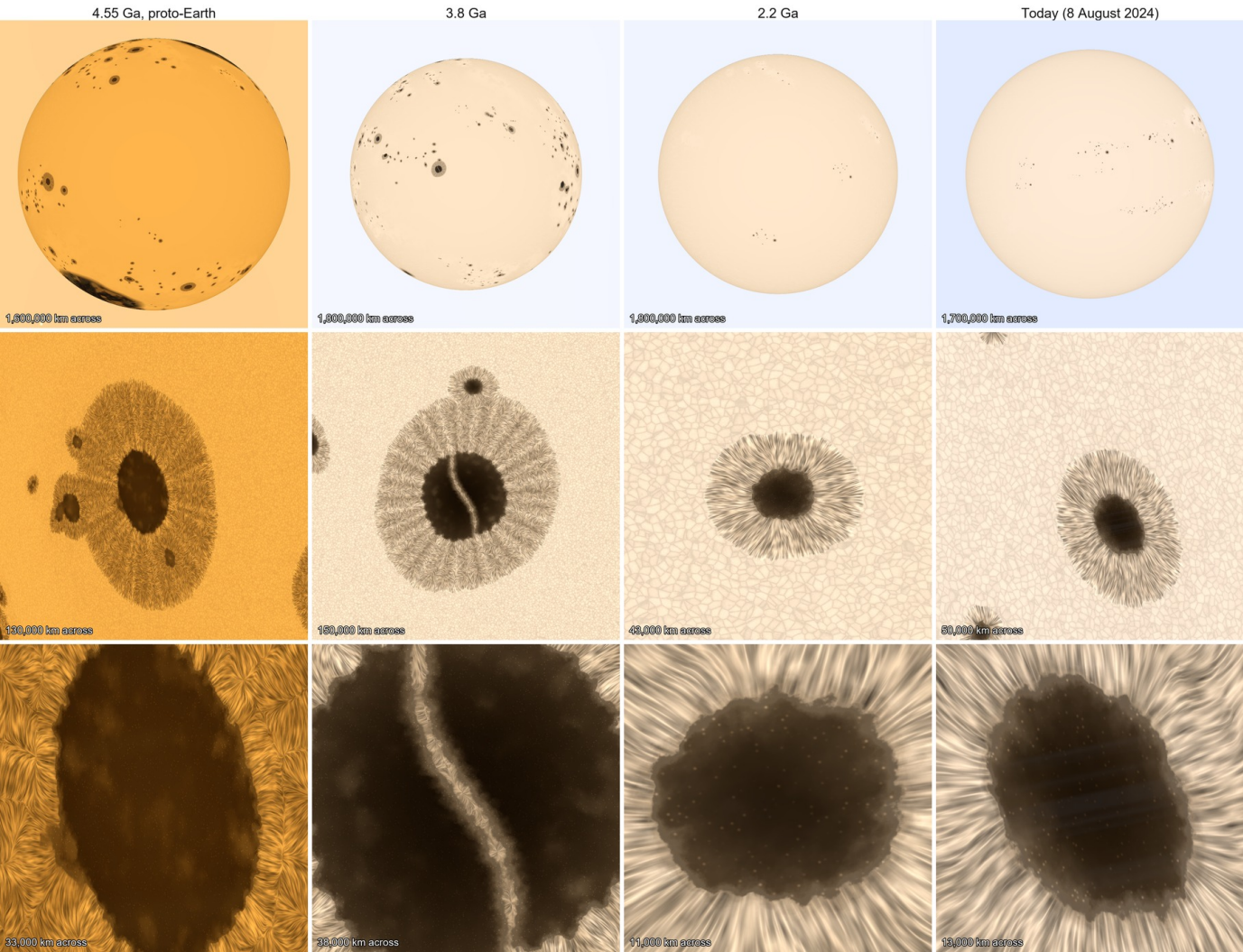


Figure 7: The Sun's surface at four epochs, as the site's telescope view draws it at noon through each epoch's air (sun_figs.py). Top: the whole disk. Middle: its largest spot group. Bottom: that group's largest umbra. Widths are in km on the Sun, since the site draws the Sun at four times its size. The 17-million-year-old Sun of 4.55 Ga, orange through the proto-Earth's dusty air, is spotted over a tenth of its surface, its spots at high latitudes and a dark cap over the pole; at 3.8 Ga spots are on the disk every day; by 2.2 Ga a few groups keep to the butterfly's latitudes; today's disk is the real cycle 25 near its maximum. Close up the structure is the same in every epoch: granulation and its network around the spots, penumbral filaments, umbral dots, and in the 3.8 Ga spot a light bridge of granules.

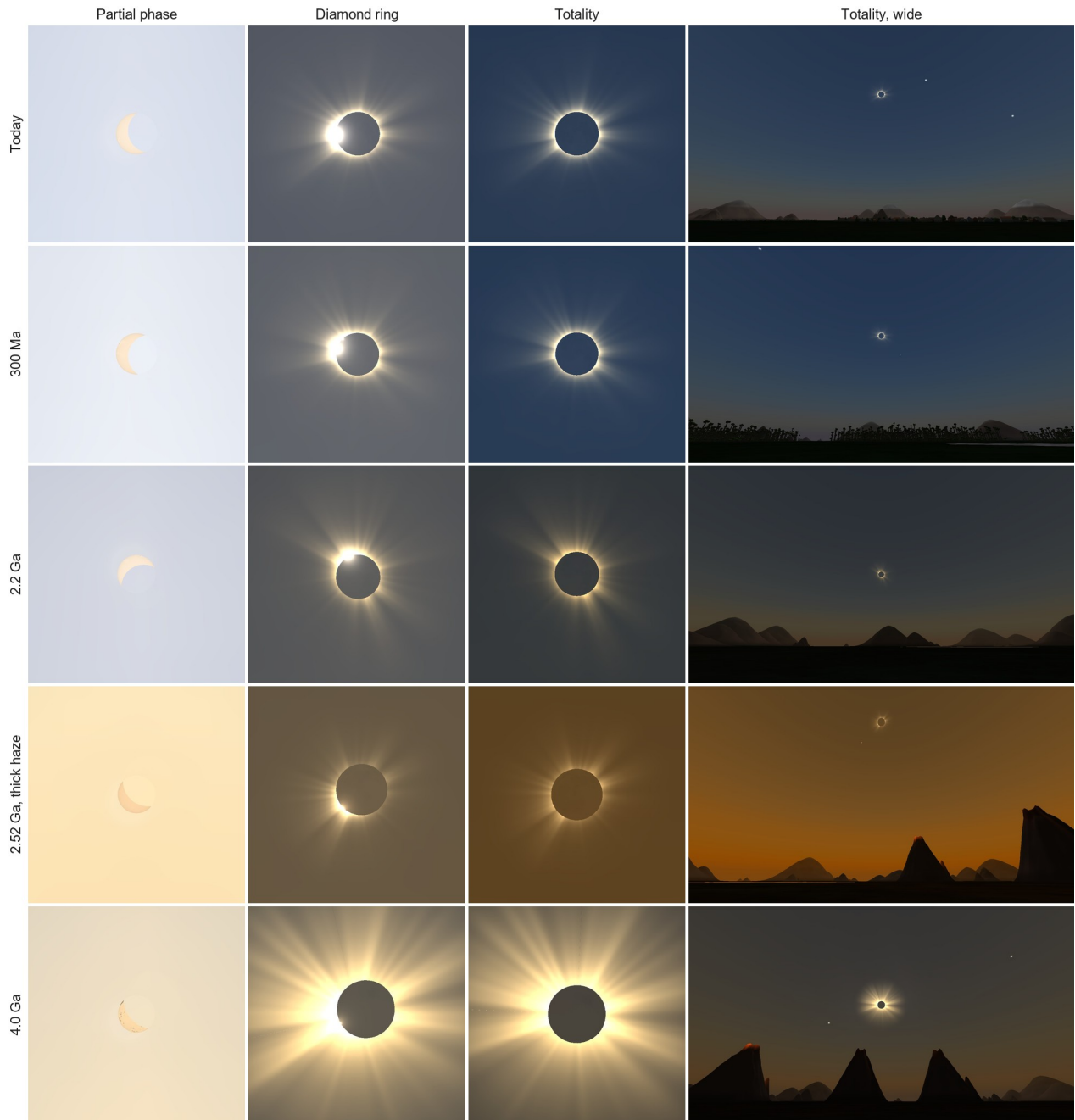


Figure 8: A total solar eclipse in five epochs, as the site's first-person view draws it: in each, the first total eclipse after October 2026 on the page's calendar with the Sun at least 25° up (today's is the eclipse of 30 March 2033), cloud cleared. Left to right: the partial phase, 70 percent of the way from first to second contact; the diamond ring, with a sliver of photosphere half a percent of the Sun's width left; mid-totality; and mid-totality in a 75° view with the horizon. The close-ups share one scale (14° high), with the Sun and Moon at four times their size as on the site, so the growing Moon shows, from about the Sun's width today to 1.15 times it at 2.2 Ga and 1.55 times at 4.0 Ga, where it hides the inner corona; each frame is exposed as the site's view adapts to its light. Totality's sky is the epoch's twilight: slate blue-gray with a sunset rim on the horizon today, at 300 Ma and at 2.2 Ga, amber over an orange horizon under the 2.52 Ga haze, which also dims the corona, and the hot young Sun's corona at 4.0 Ga is far larger and brighter. The young Sun's spots show on the crescents at 2.52 and 4.0 Ga. At 4.5 Ga the Moon is eight times the Sun's width and the corona hardly clears it.

5 The Moon

5.1 The Moon's orbit through time

The Moon raises tides on the Earth, and the tidal bulge, carried ahead of it by the Earth's spin, pulls it forward: the Moon has been receding ever since it formed, today by 3.8 cm a year, while the Earth's day lengthens. Run back, the Moon was closer and bigger, its month shorter, and the day shorter too. We take the distance from [Farhat et al. \(2022\)](#), whose tidal model fits both the present recession and the geological record of tidal rhythmites, back to 3.2 Ga, where [Eulenfeld & Heubeck \(2023\)](#) find 70% of today's distance in the Moodies Group rhythmites; older ages extend the long-term drift. At 4.5 Ga, some ten million years after the giant impact, the Moon is still at about 8 Earth radii: [Korenaga \(2023\)](#) finds that a Moon whose magma ocean was still solidifying raised little tide in itself and had receded only to 7 to 9 Earth radii by the time the ocean froze. (Table 5 gives the numbers by epoch; between the epochs the distance follows the same history, year by year.)

The day follows from the distance by holding the Earth–Moon angular momentum fixed: a closer Moon means a faster-spinning Earth. This reproduces the day lengths [Farhat et al. \(2022\)](#) give for their distances to within a tenth of an hour, 21.9 hours at 700 Ma and 15.6 hours at 2.7 Ga, and at 4.5 Ga it gives 5.9 hours. The year is the same length in seconds in every epoch, since the Earth's orbit is set by the Sun's mass, which has barely changed; so a year held 400 days in Snowball Earth, 562 at 2.7 Ga and 1,486 at 4.5 Ga. The month, by Kepler's third law, was 22.6 of today's days at 2.2 Ga and 15.3 at 4.0 Ga, still 28 to 31 of each epoch's own shorter days; at 2.7 Ga a year held about eighteen months, as tidal rhythmites suggest. At 4.5 Ga the Moon went round in 32 hours, five and a half of that epoch's days. The proto-Earth of 4.55 Ga has no Moon; how fast it turned before the impact cannot be known, and its 12-hour day is a guess.

The orbit's tilt to the ecliptic also changed. We carry today's 5.15° back along these distances with the semi-analytic tidal model of [Čuk et al. \(2016\)](#): the Earth's tides tilt the orbit less as the Moon recedes, and tides raised in the Moon itself damp the tilt, most strongly near 33 Earth radii, where the Moon's own obliquity swings large. The orbit comes out a little steeper in the past, 5.5° at 2.7 Ga and 5.8° at 4.0 Ga; Čuk et al. argue these are lower bounds, and the 17° to 30° and more that such models give for the young Moon belong before 33 Earth radii, older than any epoch here but 4.5 Ga. Inside the Laplace radius the orbit precesses about the Earth's equator rather than the ecliptic ([Tremaine, Touma & Namouni 2009](#), eq. 24): 8.4 Earth radii for the present Earth. A fluid Earth spinning in 5.9 hours carries a larger bulge, and the radius moves out by $(24/5.9)^{2/5}$, to about 15 Earth radii, so the 4.5 Ga Moon is drawn in the plane of the equator. The orbit was more eccentric too, growing from today's 0.055 to about 0.1 at 4.0 Ga ([Daher et al. 2021](#)), after it had been through the evection resonance. In the [Čuk & Stewart \(2012\)](#) example that resonance holds the eccentricity near 0.45 from about 9,000 to 70,000 years, and by 4.5 Ga tides have damped the orbit nearly round again. With the eccentricity the Moon rocks east and west each month by about twice the eccentricity in radians, $\pm 6.3^\circ$ today and $\pm 12^\circ$ at 4.0 Ga, and north and south by its obliquity, 6.7° today and 21° to 23° at 3.8 and 4.0 Ga, as it nears the Cassini-state transition; the page draws the globe on these axes, so the Moon visibly librates.

The consequences show in the sky. At 3.8 Ga the Moon is one and a half times today's width and more than twice as bright when full. At 4.5 Ga it is 4° across, seven and a half times today's width and 57 times its area, and so close that it is placed as seen from the ground: it shifts 7° against the stars between the horizon and the zenith. It crosses the sky in hours, rising and setting several times a day. In the plane of the equator, it eclipses the Sun at every new Moon for weeks around each equinox, somewhere on the Earth, and passes through the Earth's shadow, 14° across at its distance, at every full Moon.

5.2 The Moon's face

The Moon's face is the Lunar Reconnaissance Orbiter's: the Wide Angle Camera's color mosaic, toned to match a full-Moon photograph, and the Laser Altimeter's heights (NASA's CGI Moon Kit). The heights light the slopes, cast shadows toward the terminator, and shape the limb, so a zoomed crescent shows a ragged terminator and crater shadows, and the edge of the Moon in an eclipse breaks the last sunlight into Baily's beads. Five globes cover the Moon's history (Figure 11). Tycho, about 109 million years old ([Stöffler & Ryder 2001](#), from the exposure ages of [Arvidson et al. 1976](#)), is taken away with its rays for the skies older than 109 Ma. Before about 3.9 Ga the maria had not been flooded: basalts filled the great basins from about 3.9 Ga and most of them by 3.3 Ga ([Hiesinger et al. 2011](#)), so each mare darkens over 150 million years from an onset just before its oldest dated basalt. At 3.8 Ga Tranquillitatis is two-thirds dark, Serenitatis and Nectaris a third, and Imbrium and Procellarum are still bright: the familiar face is not there yet. At 4.0 Ga the near side is bright highland from limb to limb. At 3.8 Ga the eruptions themselves show: one to three fissure eruptions a lunation glow on the night side, a few to a hundred square kilometers of lava at about 1,400 K, as bright per area as the sunlit Moon and far redder, magnitude +3 to -1 as seen from the Earth.

The Moon of 4.5 Ga is not yet solid. Its magma ocean is open at the top, some ten million years after the impact (the site draws it so for the first 20 million years, then cools it into the Moon of 4.0 Ga by 4,450 Ma, its glow fading and its dark rafts graying as a crust closes over it; the times are a guess): rafts of dark quench crust and the first pale anorthosite, floating a few hundred meters to a kilometer and a half above the melt, broken by cracks and lava lakes at 1,400 to 1,600 K in four generations of floes, each a network of cracks within the last. The lava shines about as brightly per area as the sunlit Moon, so the disk glows orange by day and night alike, also inside the Earth's shadow, and the air around it carries a red aureole. The map and its relief are made up; that the young Moon looked like this is an inference from its magma ocean, not an observation.

The night side is drawn at a flat 6% of the lit side's brightness rather than with a modeled earthshine, which the spectrum readout gives instead: about 2×10^{-4} of the day side when the Earth is full from the Moon, and bluer.

5.3 Moonlight

Moonlight is the same sky model with the Moon in place of the Sun, scaled by the lunar phase (the Allen phase law with the opposition surge, as in [Krisciunas & Schaefer 1991](#)) and by the inverse square of the Moon's distance. It stays nearly the same in color from epoch to epoch but not in brightness: the full Moon lit the sky 2.2 times as brightly at 3.8 Ga and 57 times at 4.5 Ga, where it lit a 30-bar sky that, like its day sky, was a featureless peach glow.

5.4 Lunar eclipses

In a lunar eclipse the Moon passes through the Earth's shadow, which is lit only by sunlight bent into it through the Earth's limb: every sunrise and sunset on Earth at once. Its color and brightness are a measurement of the whole atmosphere at the terminator, which is why eclipses darkened after Tambora and El Chichón ([Stothers 2005](#); [Keen 1983](#)), why the eclipse of August 2008 carried the imprint of the small Kasatochi eruption ([García Muñoz et al. 2011](#)), and why the eclipsed Moon's spectrum is Earth's transmission spectrum as an exoplanet would show it ([Pallé et al. 2009](#)). The same physics, run on each epoch's air, gives the eclipse of every era.

The model (*lunar_eclipse.py*) traces rays from the Sun through the epoch's atmosphere at tangent heights from the ground to 120 km, bending with the refractivity of its gas mix and accumulating the optical depth of every component (gas, ozone, aerosol, sulfate, haze, soot) along the whole path, with today's cloud tops cutting the lowest rays. Seen from a point on the Moon, the Earth's limb at each position

Table 5: The Moon by epoch, as the site draws it. Distance in Earth radii ([Farhat et al. 2022](#); [Eulenfeld & Heubeck 2023](#); [Korenaga 2023](#) at 4.5 Ga); width and full-Moon light relative to today's; the day from the Earth–Moon angular momentum held fixed; the month from new Moon to new Moon in today's days, and in brackets in the epoch's own; the orbit's tilt from the tidal model of [Čuk et al. \(2016\)](#), in the plane of the equator at 4.5 Ga; the eccentricity after [Daher et al. \(2021\)](#). The 4.55 Ga proto-Earth has no Moon.

Epoch	Distance ($R_{\oplus}$)	Width	Full-Moon light	Day	Days a year	Month (own days)	Tilt to ecliptic	Eccentricity
Today	60.1	$1.00\times$	$1.00\times$	24.0 h	365	29.5 d (29.5)	5.15°	0.055
66 Ma	59.9	$1.00\times$	$1.01\times$	23.8 h	368	29.4 d (29.6)	5.15°	0.056
300 Ma	58.6	$1.03\times$	$1.05\times$	22.6 h	388	28.3 d (30.0)	5.18°	0.059
466 Ma	58.2	$1.03\times$	$1.07\times$	22.3 h	393	28.0 d (30.1)	5.19°	0.060
700 Ma	57.7	$1.04\times$	$1.09\times$	21.9 h	400	27.6 d (30.3)	5.20°	0.061
2.2 Ga	51.0	$1.18\times$	$1.39\times$	17.4 h	504	22.6 d (31.2)	5.37°	0.078
2.7 Ga	47.6	$1.26\times$	$1.60\times$	15.6 h	562	20.3 d (31.2)	5.46°	0.087
3.8 Ga	40.4	$1.49\times$	$2.22\times$	12.8 h	685	15.7 d (29.4)	5.75°	0.105
4.0 Ga	39.8	$1.51\times$	$2.28\times$	12.6 h	696	15.3 d (29.2)	5.80°	0.106
4.5 Ga	8.0	$7.52\times$	$57\times$	5.9 h	1,486	1.3 d (5.4)	equator	0.010

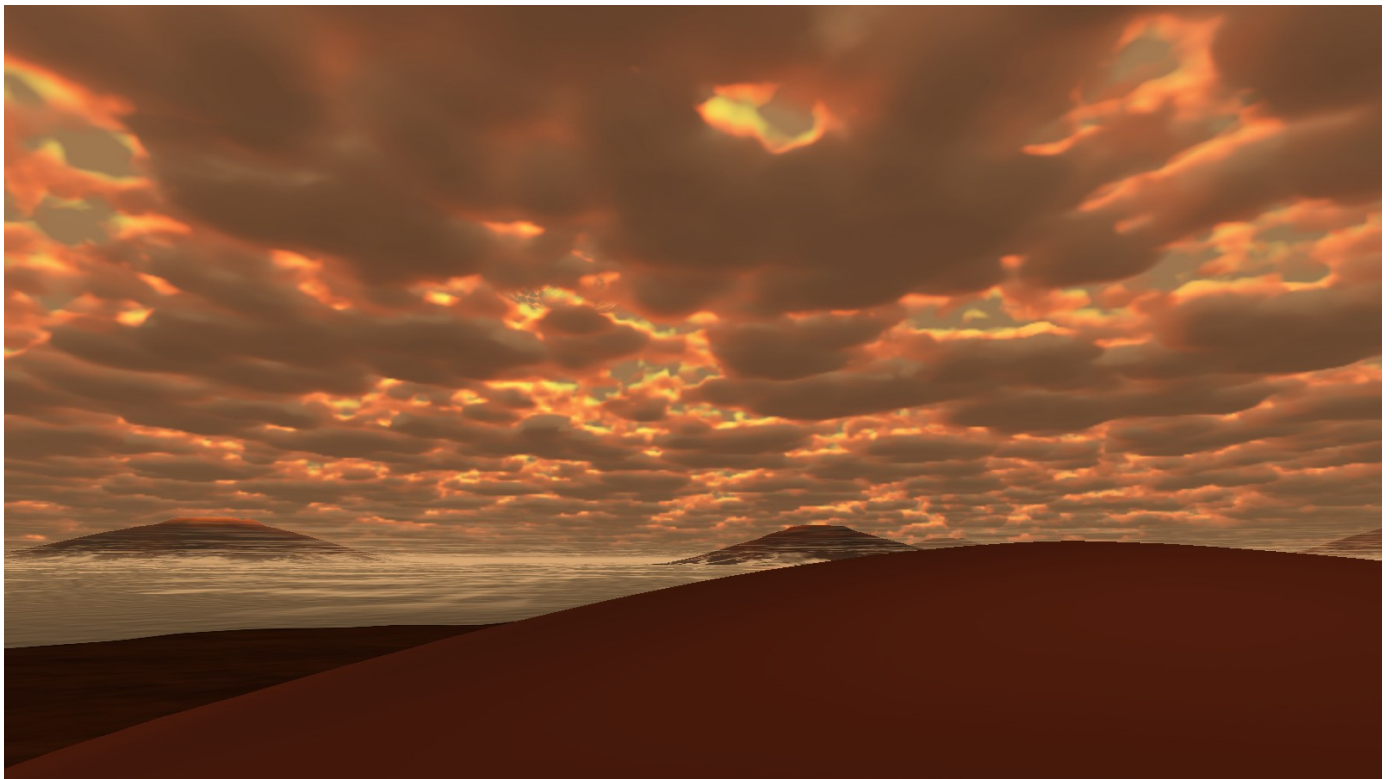


Figure 9: An evening at 4.5 Ga. Through 30 bar of CO_2 and a near-overcast deck, the molten newborn Moon, 8 Earth radii away and 4° across, glows orange through cracks in its first crust, with its red aureole, over a hot steaming sea.

angle and height shows the Sun's limb-darkened disk wherever the ray's bending puts it; summing that over the ring of the limb (Link's method; [Link 1969](#); [García Muñoz et al. 2012](#) for a modern treatment) gives the spectrum of the light at each distance from the shadow's axis, and the direct sunlight past the top of the air gives the penumbra. Today's umbra comes out a dull copper. A central eclipse puts the Moon 12.3 magnitudes below the full Moon, about $V = -0.4$, in the range observed for clear-air eclipses, with the center darkest and a paler, slightly bluish edge where ozone's Chappuis band removes the orange from the highest rays (the turquoise fringe of eclipse photographs). Before the Great Oxidation there is no ozone and that edge is orange too. A Tambora-sized sulfate veil puts the Moon near $V = +11$, a surface brightness of 27 mag/arcsec², far below the night sky: it vanishes, as it did to observers in June 1816 ([Stothers 2005](#)). The K–Pg soot and the thick Neoproterozoic haze remove it entirely; the thin haze leaves a dim brown-red Moon near $V = +5$.

Two effects are new to the deep past. The closer Moon sat nearer the Earth than the refracted light comes to a focus (about 300,000 km today, past the Moon's 384,000), so the middle of the shadow is reached only by rays skimming the ground and goes dark: at 3.8 Ga the center of the shadow is a hundred million times fainter than its edge, a dark core in a glowing ring. And the 30-bar Hadean air is so refractive that below about 19 km its rays are trapped and run round the planet, while the upper air bends light strongly enough to fill the whole umbra of a Moon some 39 Earth radii out, an even, deep red at $V = -1.7$; but the Moon of 4.5 Ga, only 8 Earth radii out, sits well inside the focus, and at mid-eclipse it is gone, $V = +12$.

The shadow's geometry follows the distances and the young Sun's size. The umbra was 3.1 Moon widths across at 4.0 Ga against 2.7 today, and with twice as many full Moons a year, total lunar eclipses came nearly three times as often, while totality itself lasted at most 105 to 109 minutes in every epoch from 4.0 Ga on (Table 6). At 4.5 Ga the Moon, inside the Laplace radius of a fast-spinning Earth, orbits in the plane of the Earth's equator, its shadow is 3.6 Moon widths across and it races through it: around each equinox every full Moon is eclipsed, some 3,900 total eclipses a century, none longer than an hour. The rate also depends on the tilt of the Moon's orbit. It was a little steeper then: integrating today's 5.145° back along the distance history with the tidal model of [Čuk et al. \(2016\)](#), in which Earth's tides flatten the orbit as the Moon recedes and tides raised in the Moon damp it, gives 5.46° at 2.7 Ga and 5.80° at 4.0 Ga (a little more for a Moon stiffer or more dissipative). The much larger tilts that model and [Downey, Nimmo & Matsuyama \(2023\)](#) need for the young Moon belong to before the Cassini-state transition near 33 Earth radii, older than any epoch here but 4.5 Ga, whose Moon is in the equator's plane (*lunar_inclination.py*).

The ephemeris is checked against the almanac. For the total eclipses of 2022, 2025, 2026 and 2029, contact times fall within 2 to 7 minutes of the NASA catalog ([Espanak & Meeus 2009](#)) and umbral magnitudes within 0.04 (for 2029 June 26, 1.831 against 1.844); over 2000–2100 the page finds 144 umbral and 84 total eclipses, against the catalog's 142 and 85. On the page the Moon is drawn for an eye adapted to its brightest part, so the umbra looks black beside the penumbra in a partial phase and glows in totality, as it does to an observer.

6 The planets and their moons

6.1 Where the planets were

The five naked-eye planets, Uranus and Neptune are placed from JPL's approximate Keplerian elements (Standish's table, valid 1800–2050) for the date and time, light-time corrected, on the same magnitude scale as the stars (Meeus's formulae with the phase angle, Saturn's rings included when there are rings, and [Mallama & Hilton 2018](#) for Uranus and Neptune), and dimmed by the young Sun's fainter light: 0.42 magnitudes at 4.5 Ga, 0.24 at 2.7 Ga. Any planet brighter than magnitude -6 lights the sky as the Moon does. Within

10,000 years of today the positions are the real ones. Further off they cannot be known: the Solar System is chaotic, its uncertainties growing tenfold every ten million years or so ([Laskar 1989](#)), and every epoch's age is uncertain by far more than any planet's period. So each planet is put at a random place on its orbit, the same for every visit to an epoch (and in the modern-era skies far from today, for each 100,000 years), and moves on with the date. The orbits' shapes are today's, known to some 50 million years and statistically before; their slow changes, which Standish's rates give for a few thousand years, are held where they are 3,000 years from today.

The two oldest skies have a different Solar System. In the reading of the meteorites' bombardment ages ([Edwards et al. 2024](#); [Liu, Raymond & Jacobson 2022](#)), the giant planets went unstable early, within the first 100 million years; the 4.55 Ga sky shows them before it, in the best starting configuration of [Nesvorný & Morbidelli \(2012\)](#): Jupiter at 5.6 AU and Saturn at 7.34 AU in a 3:2 resonance, a fifth giant at 9.62 AU, Uranus at 15.3 and Neptune at 20 AU, each in resonance with the next. The fifth giant, an ice giant like Neptune that Jupiter threw out of the Solar System in the instability ([Nesvorný 2011](#)), is named here Oceanus. We date the instability to 4.48 Ga, the latest that the dated lunar and asteroidal impact record allows ([Mojzsis et al. 2019](#)) and within the first 100 million years ([Nesvorný et al. 2018](#)), so the 4.5 Ga sky still has the earlier arrangement; the bombardment ages would put it earlier still, as the 4.55 Ga sky's account says. From 4.48 Ga on the planets are on today's orbits.

Theia, the Mars-sized body whose collision with the proto-Earth made the Moon, is a wandering planet in the skies before the impact, 4.51 Ga. Its orbit is made up, as any that would meet the Earth's will do, since where it lay is not known ([Branco, Machado & Raymond 2025](#)). Every 25 years or so it passes within a few hundredths of an AU, and at its closest it reaches magnitude -8.5 , half lit, brighter than any planet has been since, lighting the night. Its face is invented too: an airless, cratered, iron-rich basaltic crust ([Meier, Reufer & Wieler 2014](#)), its steam atmosphere lost to the young Sun within a few tens of millions of years ([Odert et al. 2018](#)), with eight great basins and a few young rayed craters.

Three more worlds of the giant impacts share the 4.55 Ga sky, all hypothetical and named here. Mercury, its core some 70% of its mass, seems to have lost most of its mantle in a collision. A single giant impact on a larger proto-Mercury ([Benz et al. 2007](#); [Chau et al. 2018](#)) seldom leaves Mercury and Venus on orbits like theirs ([Clement, Kaib & Chambers 2019](#)), but a grazing collision of two bodies of similar mass, the commonest kind in models of the planets' growth, can make Mercury ([Franco et al. 2025](#)). We draw that: until 4.54 Ga Mercury is proto-Mercury, about 0.12 Earth masses and 3,500 km in radius, 0.7 magnitudes brighter than Mercury in the same place, and the body that grazes it, Anteros, is a Mars-sized planet on an orbit from 0.39 to 0.72 AU that crosses both Mercury's and Venus's. A giant impact can also account for Venus's slow, backward spin and its lack of a moon ([Busmann et al. 2025](#)), and after the graze we let Anteros strike Venus, at 4.53 Ga. That one body did both is our choice, and its orbit and both dates are made up. From the Earth it keeps within 46 degrees of the Sun, as Venus does, at about magnitude -0.5 , and -1.6 at its brightest. Enyo is the body whose impact made Mars's crustal dichotomy: 1,600–2,700 km across for a northern Borealis basin ([Marinova, Aharonson & Asphaug 2008](#)), 1,000–1,500 km for an impact in the south ([Ballantyne et al. 2023](#)); we take 1,400 km. On a made-up orbit crossing Mars's, it reaches magnitude 1 at its best and is usually fainter than 5, and it stays until 4.3 Ga, when it makes the dichotomy and Mars's first moons. Their faces are invented as Theia's is, with heights (*embryo_maps.py*). Proto-Mercury's oldest crust is dark with graphite floated from its magma ocean ([Vander Kaaden & McCubbin 2015](#); [Peplowski et al. 2016](#)), under brighter, redder volcanic plains over a quarter of it, as on Mercury ([Denevi et al. 2013](#)), where craters dig up dark halos. Anteros's crust is basalt darkened and reddened by the young Sun's wind, with a great lava-flooded basin over one side. Enyo's is light basalt like Vesta's, with dark carbonaceous spatter ([McCord et al. 2012](#)) and basins as

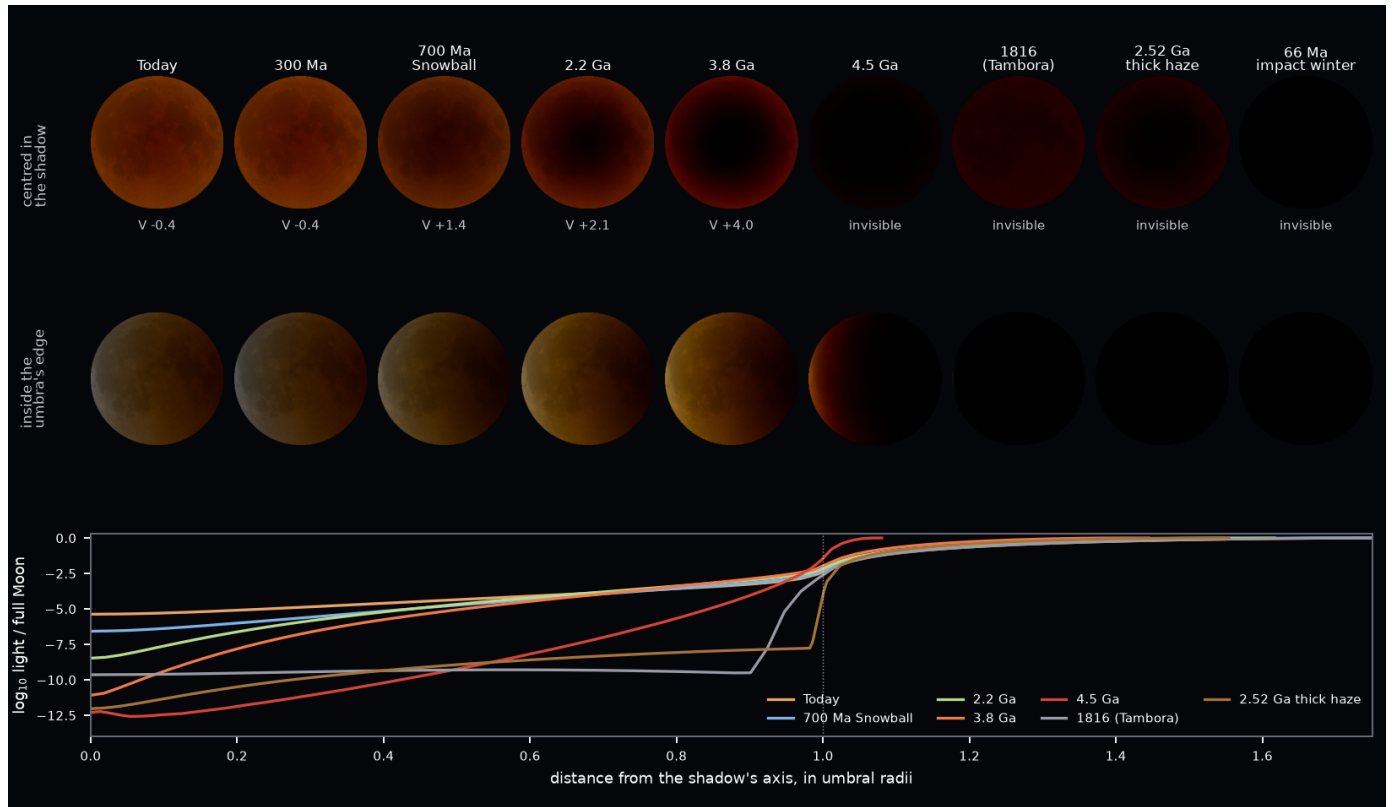


Figure 10: The Moon in the Earth's shadow at nine epochs, on today's lunar surface. Top: centered in the shadow, with its V magnitude, each drawn as the page draws it, for an eye adapted to that Moon's brightest part. Middle: just inside the umbra, its limb at 0.95 of the umbral radius, all at one exposure so their light compares: today's ozone leaves a cool gray-blue edge, the ozone-free Archean edge is orange and the Hadean's deep red, and under the Tambora veil, the 2.52 Ga thick haze and the K–Pg soot the umbra is dark to its edge. Bottom: the light across the shadow, against the full Moon, with distance in units of each epoch's umbral radius.

Table 6: Lunar eclipses by epoch. The umbra's diameter is in Moon widths at the mean distance, with Danjon's enlargement. V and the mean surface brightness are for the Moon centered in the shadow, from the model's shadow and the Moon's distance; a dark night sky is about 22 mag/arcsec². Counts are the page's own over a hundred years of dates (2000–2100), so they carry a few percent of noise from the eclipse cycles. Orbit tilt from lunar_inclination.py; at 4.5 Ga the Moon orbits in the plane of the Earth's equator, so its tilt to the ecliptic is the obliquity.

Epoch	Umbra (Moon widths)	V at mid-eclipse	Surface brightness (mag/arcsec ²)	Orbit tilt	Umbral / total a century	Longest totality (min)
Today	2.69	−0.4	16	5.15°	144 / 84	107
1816 (Tambora)	2.69	invisible	27	5.15°	144 / 84	107
66 Ma impact winter	2.70	invisible	—	5.15°	149 / 71	107
300 Ma	2.73	−0.4	16	5.18°	167 / 76	107
466 Ma	2.74	+0.3	16	5.19°	171 / 74	106
700 Ma Snowball	2.76	+1.4	18	5.20°	172 / 77	108
2.2 Ga	2.90	+2.1	19	5.37°	226 / 124	106
2.52 Ga thick haze	2.96	invisible	29	5.46°	286 / 137	109
3.8 Ga	3.09	+4.0	21	5.75°	420 / 211	105
4.0 Ga	3.10	−0.4	17	5.80°	438 / 218	106
4.5 Ga	3.59	invisible	33	23.44°	7080 / 3916	57

deep for its size as Vesta's.

The three largest asteroids are placed the same way, in every epoch: Vesta, which reaches magnitude 5.2 and the naked eye, Ceres and Pallas. Their elements are fit here to JPL Horizons over 1800–2200, with periodic terms in the mean longitude for Jupiter's pull (for Pallas, 0.9 degrees over 83 years), to a tenth or two of a degree as seen from the Sun, and their brightness follows the H, G system of [Bowell et al. \(1989\)](#) with JPL's values.

6.2 The planets close up

Zooming in acts as a telescope, gaining 5 magnitudes against the sky for each tenfold zoom (magnification spreads the sky's light and leaves a point a point), so faint moons and Uranus and Neptune come out, and Mercury and Venus show by day. Each planet is a disk of its true angular size and flattening, on its IAU pole and prime meridian, lit from the Sun's side, so the phases of Mercury and Venus show; its limb darkens by a Minnaert law. Mercury and Mars wear spacecraft maps, MESSENGER's color mosaic and Viking's, toned toward true color, with their relief from MESSENGER ([Becker et al. 2016](#)) and the Mars Orbiter Laser Altimeter: slopes lit by the planet's own law, and rims and peaks hiding the Sun, so a gibbous Mars shows the shadows of Tharsis and Olympus Mons near its terminator and a half-lit Mercury a ragged, cratered one. Venus is cloud, cream and featureless, bright in the crescent. The moons of Jupiter, Saturn and Uranus, and Triton, have their own maps (Galileo, Voyager and Cassini mosaics), and cast their shadows on their planets, go dark in the planets' shadows, and pass behind and in front of them. Of Uranus's five, as of Triton, Voyager 2 saw only the southern halves, lit in 1986; the rest is filled in smooth, and since Uranus's north has turned toward the Sun and the Earth, it is mostly that blank half that faces us now. Uranus has its ten narrow rings, as [French et al. \(2024\)](#) fit them to thirty years of stellar occultations: each the ellipse of its orbit, its periape precessing (the ϵ ring's 406 km off-center, turning once in nine months), its width growing from periape to apoapse (the ϵ ring's from 20 to 97 km) and its depth thinning to match, with optical depths after [Esposito et al. \(1991\)](#). The particles are as dark as charcoal, so even the ϵ ring is only a faint thread at the deepest zoom, as it is in a real telescope; the dusty rings, a hundred-thousandth as thick, are left out. Ceres and Vesta wear Dawn's Framing Camera mosaics and stand on its shapes: each is drawn as the spheroid that fits its shape best (Ceres 482 by 446 km, matching [Park et al. 2016](#); Vesta 281 by 226 km), with what is left of the shape, up to 23 km on Vesta, as relief that lights the slopes and also bends the outline of the disk, so Vesta's south, cut by its great basins, shows flattened and lumpy. Phobos has the Mars Express map and shape the same way, though it is never more than a few pixels. Proto-Mercury, Anteros and Enyo wear their invented maps and heights as Theia does. Pallas, which no spacecraft has visited, is the spheroid of the shape from [Marsset et al. \(2020\)](#), in its own faintly blue tint. Figure 11 shows every rocky surface the site draws.

6.3 Jupiter

Jupiter close up is drawn, not mapped: its clouds change too fast for any one map to stand for an epoch. The bands lie where the Cassini wind profile ([Porco et al. 2003](#)) puts its jets, and the clouds are a tracer stirred by eddies: each point is followed back along the streamlines of a stream function of noise, three octaves of cells three times longer along the winds than across, renewing at different times, its strength greatest in the belts and toward the poles and coming and going in storm patches some 45° long. The flow keeps area, so the belts and zones and the finer banding within them marble into curls and filaments rather than creases, and the jets' own shear draws them out along the bands. Along each boundary between a belt and a zone, Kelvin–Helmholtz billows roll up, turning the way of the shear there. Dark festoons trail from the North Equatorial Belt into the Equatorial Zone with blue-gray hot spots at their heads; dark barges sit on the belt's northern edge, and white ovals in the South South

Temperate Belt. The tracer approach follows the flow-field techniques of [Dziewanowski \(2024\)](#).

The Great Red Spot is a vortex in the same flow: an anticyclone turning the clouds along its ellipses, faster toward its edge, with a slight inflow that draws belt and zone onto its rim as spiral arms, and its turbulent wake to the west. Its history is the observed one. It was first seen for sure in 1831 (Cassini's "permanent spot" of 1665–1713 may have been another storm), so the 1816 sky has none. Its longitude follows the measured record (Peek's for 1831–1952, JUPOS since), and its size the fits of [Simon et al. \(2018\)](#) from 1979, 405.0 – 0.1939 Y degrees long and 107.2 – 0.0483 Y wide, and before 1979 a steady shrinking from about 35° long in the 1880s. The fits meet in a round spot 8.4° across in 2045, and it is held there for 2100: whether it shrinks on, steadies or fades is not known. It was reddest in 1879–1882 and has deepened again since 2014. In the deep past there is no Red Spot: storms like it come and go over centuries.

6.4 Saturn and its rings

Saturn close up is drawn as Jupiter is, a tracer stirred by the same flow, with its own winds, bands and colors. The winds are Cassini's at the cloud tops in 2004–2009 ([García-Melendo et al. 2011](#)), fit by twenty Gaussian jets to 6 m/s rms in System III, which also turns the planet: the broad equatorial jet near 400 m/s, and narrower jets alternating with latitude toward the poles. The belts lie where the wind falls off poleward, as Jupiter's do, the broad pair at 18–32° and fainter, narrower ones beyond. Saturn's haze mutes all of it, so the eddies stir about half as hard as Jupiter's, the billows turn less, and the hues vary a half to a third as much. Around the north pole the jet at 78°N meanders in a standing wave of six, the hexagon ([Godfrey 1988](#)), golden inside in the northern summer and bluish gray in the winter; both poles have a vortex with a dark eye and a bright wall, a thin ribbon wave runs along the jet at 47°N, and small bright storms rise in Storm Alley near 40°S. The winter hemisphere, out of the Sun, shows bluish at any size, as Cassini saw the north before 2009. That change lags the season by several years, and the lag is not drawn.

Saturn's rings are drawn from the Cassini radio occultation of 3 May 2005 ([Marouf et al. n.d.](#)), its optical depth at 10 km resolution from the C ring to the outer A ring, corrected to visible light in the C ring, the Cassini division and the outer A ring by the same occultation's Ka band, which sees the sub-centimeter particles the X band misses (in the outer A ring [Jerousek et al. 2016](#) find them too), with the F ring added. Each ring is a single-scattering layer (as [Cuzzi et al. 1984](#)): lit from the Sun's side it shines by its depth and particle brightness, the A ring 0.7 of the B ring's and the C ring and Cassini division half of it and grayer; seen from the unlit side only light passing through it shows, so the B ring is black and the C ring and Cassini division glow. The rings shadow the globe, and the globe shadows the rings with its oblate outline and a penumbra the Sun's width. Near the equinoxes, when the Sun is low over the rings, they shadow the moons too: a moon passing behind them is banded by their shadow and dimmed by what they let through, Mimas by up to 4 magnitudes deep in the B ring's. Edge-on, the rings thin below a pixel.

The rings are young. How young is still argued, from tens to a few hundred million years ([less et al. 2019](#); [Kempf et al. 2023](#)), and we adopt the account of [Wisdom et al. \(2022\)](#): an icy moon the size of Iapetus, named Chrysalis, orbiting between Titan and Iapetus in a 3:1 resonance with Titan, was torn apart roughly 100 to 200 million years ago, about 160 million years ago in the case they illustrate, freeing Saturn's tilt from Neptune's pull and making the rings of its debris. We draw that illustrated case, so the rings appear 160 million years ago, and before them Chrysalis is a moon of magnitude 13 to 14 beside a ringless Saturn, from 300 million years back. Younger rings are drawn more massive and cleaner: their depth grows with youth as $\text{age}^{-0.75}$, between ring-rain losses ([O'Donoghue et al. 2019](#); [Waite et al. 2018](#)) and viscous spreading ([Salmon et al. 2010](#)), half again today's at 66 Ma, and the meteoroid darkening of the C ring and Cassini division ([Cuzzi & Estrada 1998](#)) is two fifths of today's.

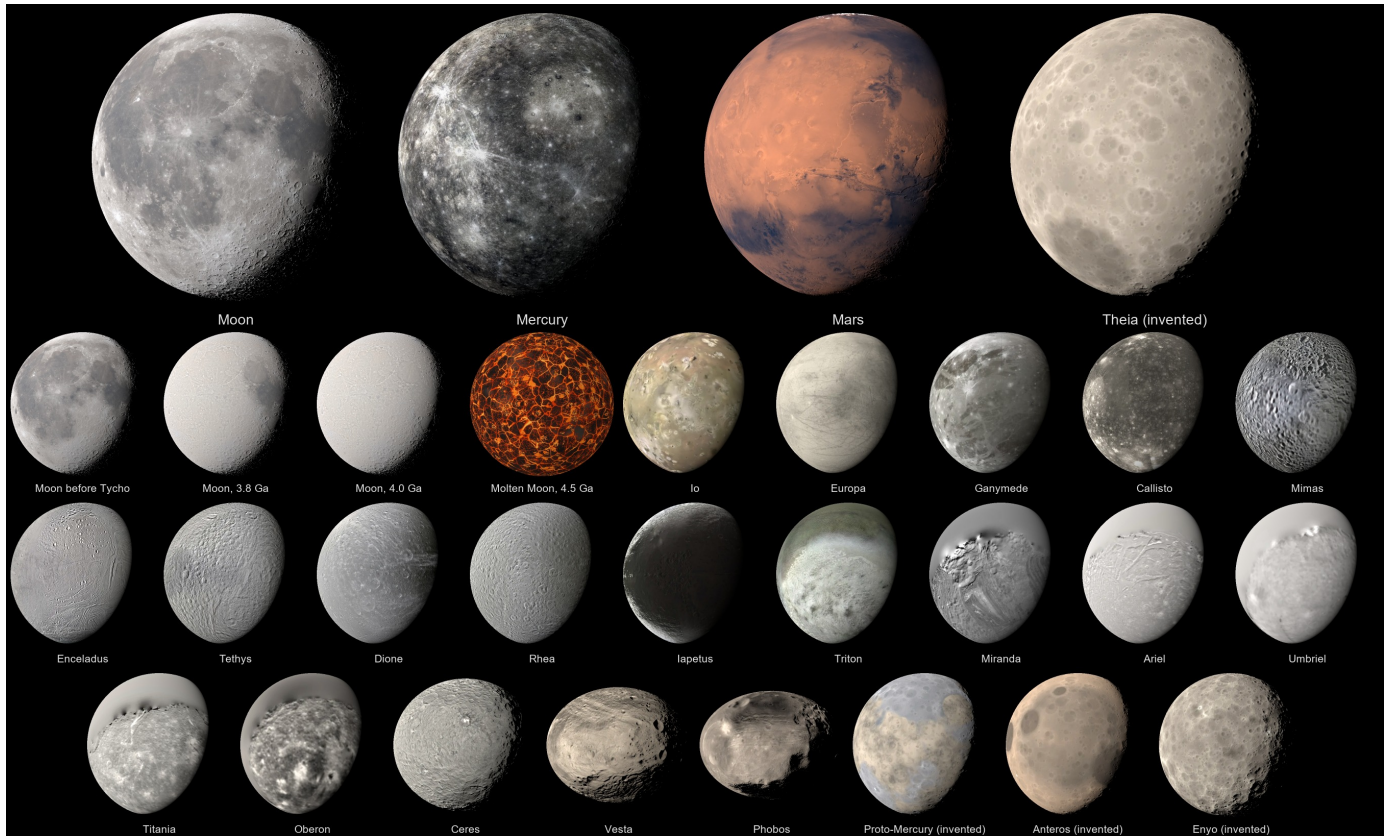


Figure 11: The rocky surfaces the site draws, each its own map on a globe lit from the left (surface_montage.py). The large panels are the four bodies drawn with heights as well, shaded by their slopes at true scale: the Moon, the Lunar Reconnaissance Orbiter's Wide Angle Camera color mosaic and Laser Altimeter heights (NASA's CGI Moon Kit); Mercury, the USGS MESSENGER MDIS color mosaic and MESSENGER heights (Becker et al. 2016); Mars, the USGS Viking color mosaic and the Mars Orbiter Laser Altimeter's gridded heights; and Theia, invented from what it was likely made of (Meier, Reufer & Wieler 2014). Proto-Mercury, Anteros and Enyo, the 4.55 Ga sky's other invented worlds, are drawn small, shaded by their heights. The Moon's older faces are today's with Tycho and its rays removed and the maria part- or un-flooded (Hiesinger et al. 2011), on the same heights; the molten Moon is a model of its magma ocean, glowing by its own light. Io, Europa, Ganymede and Callisto are the USGS Voyager and Galileo SSI mosaics; Mimas, Enceladus, Tethys, Dione, Rhea and Iapetus are Cassini color maps (NASA/JPL-Caltech/SSI/LPI, Schenk); Triton is Schenk's Voyager 2 map, its north, dark in 1989, filled in; Miranda, Ariel, Umbriel, Titania and Oberon are the USGS Voyager 2 mosaics (T. Becker), their southern halves only, shown from below. Ceres and Vesta are Dawn's Framing Camera mosaics and Phobos the Mars Express SRC mosaic (DLR, USGS), each on the spheroid the site draws it as and shaded by its shape's heights over it (Vesta's north and Ceres's far south, dark when Dawn mapped them, filled in). All are toned toward true color, and each body is shown at its own exposure, so the panels do not compare in albedo.

Both are guesses. Saturn's pole precesses once in about 1.87 million years (Ward & Hamilton 2004), so the rings open from a different direction at each time: turned by the known rate over the last ten million years, at random before.

6.5 Neptune's clouds

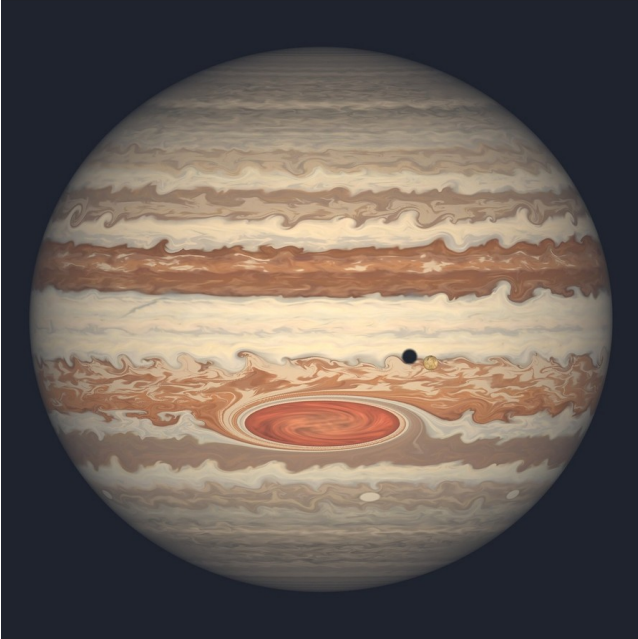
Neptune close up is drawn the same way, a tracer in its own flow. The winds are Voyager 2's cloud-tracked profile (Sromovsky et al. 1993): retrograde at 400 m/s at the equator, prograde at 250 m/s near 70°, in System III, the 16.11-hour radio period that also turns the planet. Its deck is smooth, so the eddies stir it only lightly and no billows roll up between bands. Its color is the true one, a pale greenish blue only a little bluer than Uranus's (Irwin et al. 2024), not the deep blue of Voyager's contrast-stretched images. On it are bright clouds of methane ice, in streaks drawn out by the shear of the winds that carry them, at southern mid-latitudes, near 30°N and near 70°S, each lasting some days; and the dark wave circling near 60°S, wandering a few degrees in latitude and drifting 4.87° a day in System III, with a bright band just north of it (Karkoschka 2011; Chavez et al. 2023). Dark vortices come and go, a new one every four to six years, each lasting about two (Hsu et al. 2019): deep-blue ovals with bright methane clouds along their poleward edges, turning as anticyclones and drifting with the wind at their latitude. The Great Dark Spot that Voyager 2 found is drawn as it was, at 22°S, 13,000 by 6,600 km, from late 1988 until it was gone in 1994 (Smith et al. 1989). At other times a vortex is drawn at random as their rates and sizes have it, since where one was on any given day is not known.

6.6 The giants when young

The giant planets were warmer when young, and their clouds were different. Each cools as it ages: we take its intrinsic temperature, the effective temperature its own heat alone would give it, to fall as the age to the -0.29 , a power-law fit to the cooling tracks of Burrows et al. (1997), scaled to today's (98 K for Jupiter, 78 K for Saturn, 53 K for Neptune, from the effective temperatures Voyager measured, Hanel et al. 1981, 1983 and Pearl & Conrath 1991, less the sunlight's share), and add the young Sun's light at each planet's distance. For planets of these masses the hot and cold starts of formation meet within a few tens of millions of years (Spiegel & Burrows 2012), so the history is surest over the last four billion years and least sure in the oldest sky. Then Jupiter's effective temperature was near 500 K in the 4.55 Ga sky, 330 K in the 4.5 Ga sky, 185 K at 4.0 Ga and 170 K at 3.8 Ga, against 124 K now; Saturn's 395, 265, 145 and 135 K, against 95; Neptune's 270, 180, 98 and 90 K, against 59. Uranus is drawn as it is now: it gives out too little heat for any model that starts it hot (Fortney et al. 2011), and how warm it was is not known.

A cloud deck forms where the air is cold enough for its gas to condense, and the coldest air, at the top of the troposphere, is near 0.85 of the effective temperature, so as each planet cooled its clouds formed in turn from the bottom up; young, Jupiter and Saturn had no ammonia clouds and a top deck of water clouds, and the ice giants' clouds lay higher (Fortney et al. 2011). We draw three stages. Above about 165 K Jupiter and Saturn have no ammonia ice on top and show the NH₄SH haze beneath, paler and less colored, as Jupiter is at 4.0 and 3.8 Ga; above about 85 K Neptune has no methane ice, no bright streaks, and shows its H₂S deck higher up, as pale a cyan as Uranus, whose top deck is H₂S now (Irwin et al. 2018), as Neptune is at 4.0 and 3.8 Ga. Warmer still, above about 230 K for

1879: the Red Spot at its largest



2026

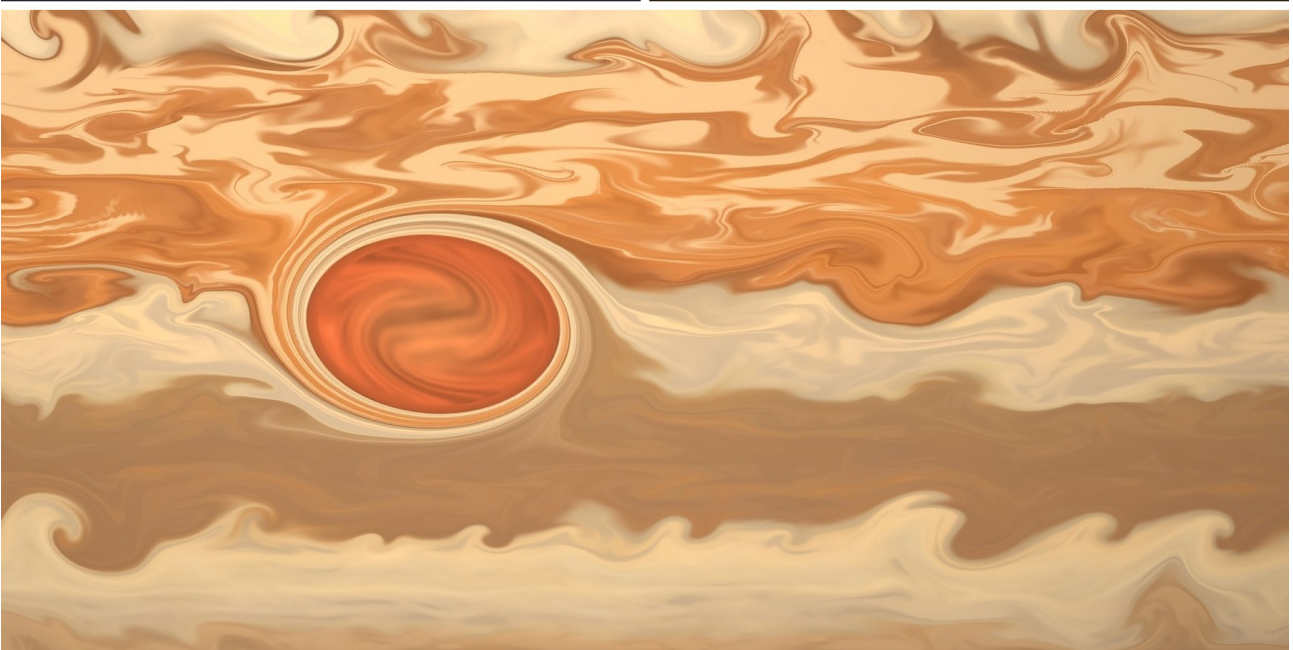
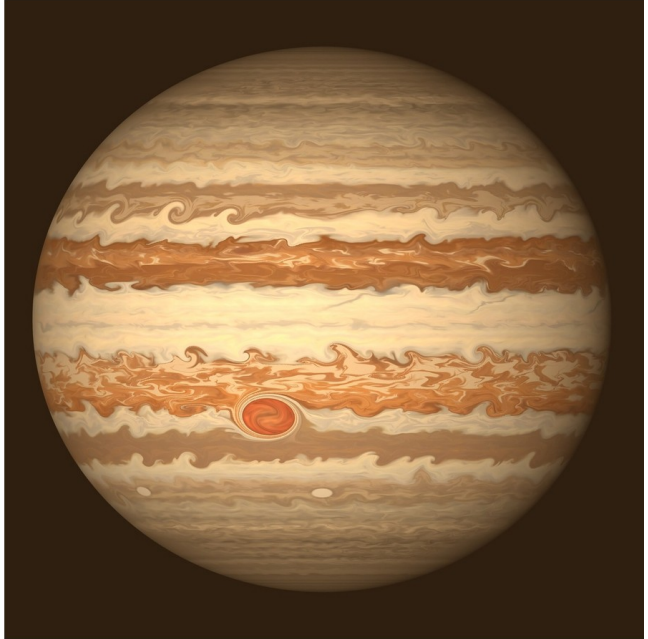


Figure 12: Jupiter close up, as the site's telescope view draws it, each view turned so the equator lies level, north up. Top: the Great Red Spot at its largest, about 35° long in 1879, when it was also reddest, and in 2026, about 12° long; in each Jupiter is shown on a night when the spot faces us. Bottom: the 2026 spot close up, a vortex in the same flow as the belts and zones around it, which eddies marble and Kelvin–Helmholtz billows roll along their edges.

the gas giants and 155 K for the ice giants, the top is a high deck of NH₄SH and water clouds, bright and near white, Sudarsky et al.'s (2000) class II: Jupiter and Saturn in the 4.5 Ga sky and the ice giants in both of the oldest, their bands showing more in brightness than in hue, the ice giants' storms of moist convection rising bright out of their mid-latitudes. Above about 380 K water no longer condenses high up and the planet is clear, their class III, a dark azure of Rayleigh scattering and methane absorption: Jupiter in the 4.55 Ga sky, and most of Saturn. Each planet's point is tinted and brightened or dimmed with its disk, and its spectrum's reflectance mixed toward the stage's: flatter and gray for the NH₄SH and water decks, with shallower methane bands above the higher clouds, and blue and dark in the red, with deep methane bands, when clear.

Oceanus, of about Neptune's mass, cools as Neptune does; nearer the Sun, at 9.6 AU, its effective temperature is 270 K in the 4.55 Ga sky and 180 K in the 4.5 Ga sky, so in both it has the high bright deck of NH₄SH and water clouds, a pale banded cyan. Its bands are laid out as the ice giants' circulation runs, air rising at mid-latitudes, where clouds are thick and bright, and sinking at the equator and poles, where they are thin (Fletcher et al. 2020): a broad darker equatorial belt, bright zones from about 18° to 45°, narrower belts near 50° and darker polar caps, carried and stirred as Neptune's are, in Neptune's winds, with bright storm tops in the rising zones of both hemispheres. Its day, unknown, is taken as 16 hours. Through the tens of bars of CO₂ of the 4.5 Ga sky none of this can be seen from the ground.

6.7 The planets' moons

The moons with fitted orbits, fitted here to JPL Horizons over 1980–2060, are Io, Europa, Ganymede and Callisto; Mimas, Enceladus, Tethys, Dione, Rhea, Titan and Iapetus; Miranda, Ariel, Umbriel, Titania and Oberon; Triton; and Mars's Phobos and Deimos. Most hold to a tenth of a degree. Iapetus's two faces show: its trailing side is ten times brighter than its leading side, so it is magnitude 10.2 at western elongation and 11.9 at eastern. The planets' moons also change with the time. Triton, retrograde, was captured in the giant-planet instability, so the skies before 4.48 Ga lack it, and Neptune has instead a family of regular moons, here named Kymo, Galene, Thetis and Amphitrite, drawn like Uranus's four largest at the same distances: Rufu & Canup (2017) find that a system no heavier than Uranus's fits best, and that capturing Triton scattered and destroyed it. Mars, from 4.3 to 3.5 Ga, has Harmonia (named here), the moon of some twenty times Phobos's mass at 3.3 Mars radii that Ćuk et al. (2020) find tilted Deimos's orbit, one generation of Mars's cycle of rings and moons (Hesselbrock & Minton 2017). Phobos is falling toward Mars: its tidal acceleration, half the rate its mean motion grows, is 1.258×10^{-3} degrees per year squared (Brožović, Jacobson & Park 2025), which is put back into its fitted longitude, so its place stays right to a few hundredths of a degree across centuries rather than drifting by degrees. Back in time, with Mars's tidal lag held fixed, its orbit grows as the 2/13 power of $1 + t/38$ Myr, to 3.2 Mars radii at 66 Ma against 2.77 now; Deimos, beyond the synchronous orbit, was only some 130 km nearer at 3.8 Ga. Both of Phobos's histories fit its orbit (Ćuk, Anand & Minton 2025): formed early just inside the synchronous orbit, or about 100 million years ago at the Roche limit as the latest moon of the ring cycle. The site follows the second, as its Harmonia does, so Phobos appears only in the skies of the last 100 million years, and Deimos from 4.3 Ga on.

7 The stars and the Galaxy

7.1 The stars moved back

Today's sky has the thousand brightest stars of the Yale Bright Star Catalogue (Hoffleit & Warren 1991), down to about magnitude 4.6, carried to the year shown by their motion and precession, each tinted by its color temperature and shown only when it is brighter than the naked-eye limit for the sky around it, so stars come out one by one in twilight and cities keep only the brightest. The Earth's axis turns by the long-term precession of Vondrák, Capitaine & Wallace (2011), good to a degree or so over 200,000 years either way: Polaris is the pole star only for a few thousand years, and Vega takes its place 12,000 years from now. Each epoch's own year has today's axis, since its phase long ago cannot be pinned down; beyond 200,000 years from it the axis turns on at the same rate and its tilt rocks between 22° and 24.5° on the 41,000-year cycle. Going back, the stars move, and how far the site can follow them sets two kinds of sky.

Over the last two million years, and the 250,000 ahead, every catalog star moves in a straight line from its Hipparcos parallax, proper motion and radial velocity (the XHIP compilation of Anderson & Francis 2012), brightening or fading as its distance changes, and the site shows the thousand brightest of the year: today's thousand and 732 others that were among them at some time over that span. Over two million years the Galaxy's pull bends the stars' paths by only a few parsecs. The sky is recognizable but rearranged. At 1.78 Ma Canopus is the brightest star, -1.6 , and Sirius, far away then, is fourth magnitude; at 342 ka Aldebaran, near its closest pass, outshines everything at -1.5 , and Sirius is $+0.8$; Sirius itself is brightest, about -1.6 , some 60,000 years from now. Constellation figures move with their stars, and a line is dropped once its stars have drifted three times today's distance apart.

Further back the lines no longer hold, and none of today's neighbors was near the Sun. Between 1.9 and 2.2 million years ago, at a time of its own, each real star fades out over 50,000 years and gives way to stand-ins of its kind: stars of its absolute magnitude, color and spectral type passing the Sun one after another on straight lines at 15 to 40 km/s, as the nearby stars' speeds relative to the Sun run, each nearest the Sun at today's star's distance and so as bright as it, toward the galactic latitude it has today and at a random longitude. Each passage lasts the time it takes to go twice that distance, from half a million to twenty million years, and fades into the next, so the deep sky changes as fast as the nearby stars move and never all at once. The stand-ins' labels give the type they copy, not a name. The sky's statistics are right; its patterns are invented, as they would be for any reconstruction that far back. The stars that outshone Sirius in the last ten million years (below) are traced through the Galaxy for the report; on the site, those of the last two million years show at their brightest.

7.2 Stars brighter than Sirius

Sirius, at magnitude -1.46 , is the brightest star in today's night sky, but it has not always been. The Sun's neighbors drift past it at tens of kilometers a second, so a star a hundred parsecs away now may have passed within a few parsecs of it a few million years ago. Tracing every Hipparcos star that has a radial velocity back 10 Myr through the Galaxy, with 2,000 draws over each star's measurement errors, finds eleven that outshone today's Sirius (Table 7). The brightest is θ Columbae, a fifth-magnitude star today, which passed about 2 pc from the Sun 4.7 million years ago and peaked near magnitude -5 , as bright as Venus at its best; Gaia DR3 astrometry (Gaia Collaboration 2023) gives the same (-5.2 at 2.1 pc, 5.1 million years ago). ϵ Canis Majoris reached -4.35 4.4 million years ago (its spell as the brightest star has been known since Tomkin 1998, who gave -4.0 at 4.7 million years), and β Canis Majoris -3.6 at the same time. From about 3.5 to 5 million years ago the night sky held at least two stars brighter than any star today, and at times three.

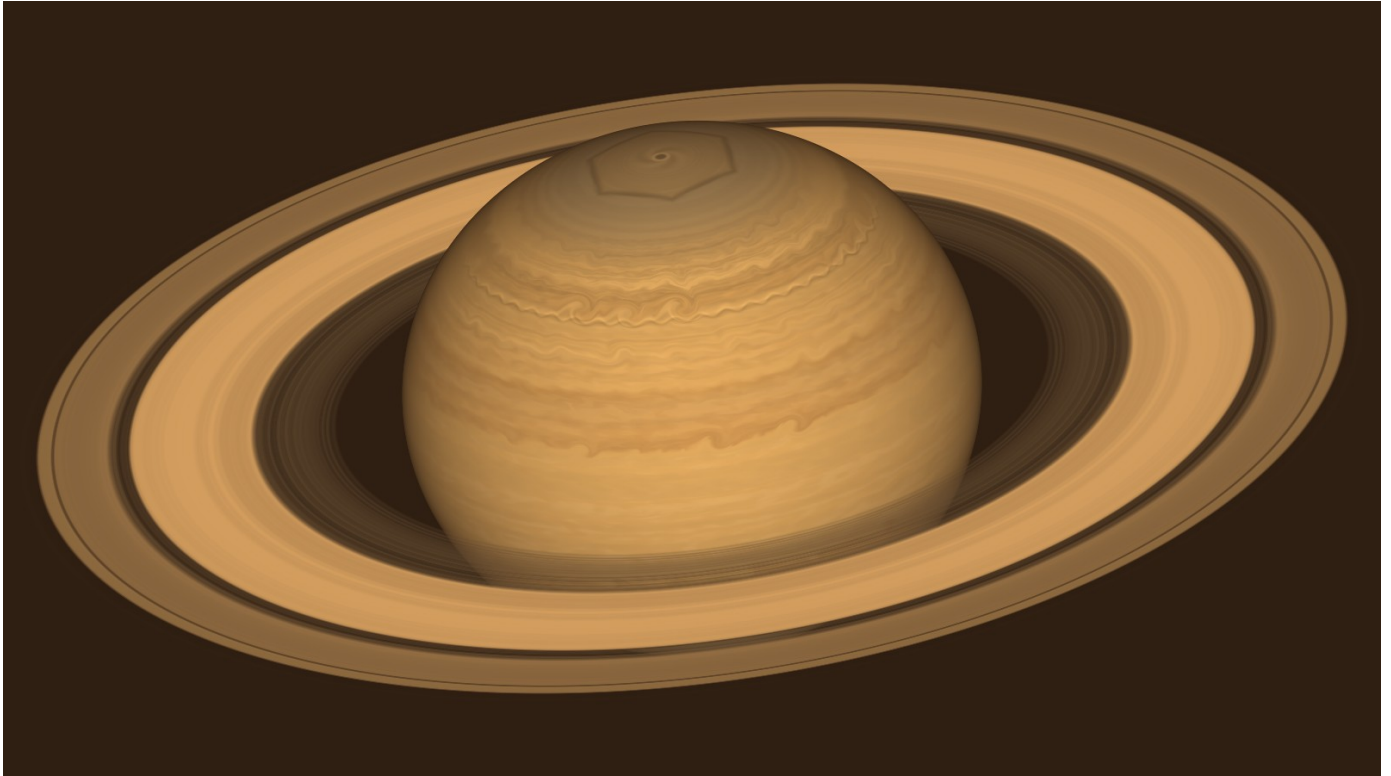


Figure 13: Saturn close up in the modern sky on 15 June 2017, at opposition, its rings filling the site's telescope view. The north pole is tilted 27° toward us, showing the hexagon around it, golden inside in the northern summer, with the polar vortex at its center. The belts are stirred by the flow drawn for Jupiter under Cassini's winds, calmer and muted by the haze. The rings are drawn from the Cassini occultation profile with single-scattering photometry; at opposition the globe's shadow on them lies hidden behind it.

Table 7: Stars that outshone today's Sirius ($V = -1.46$) in the last 10 million years, traced back through the Galaxy from Hipparcos astrometry (XHIP; [Anderson & Francis 2012](#)) with 2,000 draws over the measurement errors. Peak magnitudes are medians with the 68% range; the last column is the fraction of draws brighter than Sirius today. Brightness changes with distance only.

Star	Type	Today: V, pc	Peak V (68% range)	Closest (pc)	Myr ago	Brighter than Sirius
θ Columbae	B8:IV	5.00, 221	-5.00 (-5.77 to -4.41)	2.2	4.73	100%
ε Canis Majoris (Adara)	B1III	1.50, 124	-4.35 (-4.44 to -4.26)	8.4	4.42	100%
β Canis Majoris (Mirzam)	B1III	1.98, 151	-3.58 (-3.72 to -3.45)	11.7	4.35	100%
ρ Orionis	K0 III	4.46, 105	-3.16 (-4.24 to -2.40)	3.1	2.54	100%
Algol	B7V	2.09, 28	-2.88 (-4.65 to 2.09)	2.9	5.07	62%
ζ Leporis	A2IV-V(n)	3.55, 22	-2.54 (-2.63 to -2.43)	1.3	0.85	100%
ν Puppis	B7III	3.17, 114	-2.42 (-2.64 to -2.22)	8.7	3.56	100%
ζ Sagittarii (Ascella)	A2.5Va	2.60, 27	-1.97 (-2.07 to -1.87)	3.3	1.05	100%
Canopus	A9II	-0.62, 95	-1.92 (-2.01 to -1.82)	52.2	3.18	100%
Aldebaran	K5III	0.87, 20	-1.50 (-1.53 to -1.47)	6.8	0.33	92%
ζ Canis Majoris (Furud)	B2.5 V	3.02, 111	-1.47 (-1.87 to -0.94)	14.0	3.27	51%

These stars now lie in Columba, Canis Major and Puppis because that is the solar antapex: the Sun moves toward Hercules at about 20 km/s relative to its neighbors, so the stars it has passed end up behind it. The closest pass, ζ Leporis at 1.3 pc 850,000 years ago, came as close as α Centauri is now, far too distant to disturb the planets. Only distance changes the brightness here. ε and β Canis Majoris are giants 12 to 22 million years old and were probably a few tenths of a magnitude fainter then. Algol's radial velocity (3.7 ± 3.9 km/s, hard to measure in an eclipsing binary) is too uncertain to say whether it passed within 1.3 or 28 pc of the Sun. Rigel, Saiph, Mintaka, Alnitak and ξ Persei also come out bright, but 6 to 10 million years ago, about their own ages, so they are left out. The site's sky shows the peaks of the last two million years, where its stars move along these lines: ζ Leporis at -2.5 about 850,000 years ago, ζ Sagittarii at -2.0 about a million years ago and Aldebaran at -1.5 about 330,000 years ago. The older peaks fall before then, in its stand-in sky.

7.3 The Milky Way, nebulae and galaxies

The Milky Way is a model in galactic coordinates rather than a photograph: a disk and bulge, the Sagittarius and Scutum star clouds, the Great Rift from Cygnus to Sagittarius, the Coalsack and the Ophiuchus and Taurus dust, peaking at 20.2 mag/arcsec² in the Sagittarius star cloud (Leinert et al. 1998), and shown only in a dark sky. Its color is that of its stars: old ones, and young ones in a layer a few degrees thick that is richest along the spiral arms seen end on, in Cygnus and Carina, and absent from the bulge, all reddened by the band's own dust (Cardelli, Clayton & Mathis 1989), so Cygnus is grayer and the edges of the Great Rift and the Coalsack browner. In the older skies its brightest part lies where the Galactic center then lay as seen from the Sun, from the Sun's orbit traced back through the same model Galaxy, and the band shifts by a few degrees with the Sun's height above the plane: at 66 Ma the Sun was 100 pc north of it. Beyond about a billion years the Sun's place on its orbit is only nominal. The Galaxy itself changes too. The Sun was born about 5 kpc from the center and has since migrated out to 8.2 kpc (Frankel et al. 2018; Lu et al. 2024); the disc grew from the inside out, its half-mass radius by 43% over 7 Gyr (Frankel et al. 2019); its stars were younger, so the disc was thinner and bluer and its bulge less faded, following the star formation history measured from Gaia (Snaith et al. 2014; Mor et al. 2019; Gallart et al. 2024); and there was more gas, so more dust (Genzel et al. 2015). Seen from the inner disc 4.5 Ga, the band was little brighter along the plane, where the extra dust hid the extra stars, but it was broader, its glow a magnitude brighter 20° from the plane, and browner, the bulge behind more dust. Dark clouds last only tens of millions of years and spiral arms come and go, so before 30 Ma the band's rifts, star clouds and young-star fields are stand-ins of the same kind, not today's.

The 34 nebulae and galaxies that binoculars show under a dark sky are drawn from survey photographs, their stars taken out, each scaled to its catalog magnitude and surface brightness, and turning into its photograph when zoomed. They change with the epoch. The Andromeda and Triangulum galaxies fall toward the Milky Way on a timing-argument orbit (van der Marel et al. 2012; Kahn & Woltjer 1959), so at 4.5 Ga Andromeda is three quarters of today's size. The Large Magellanic Cloud is on its first infall (Kallivayalil et al. 2013), traced back through the Galaxy's halo with dynamical friction: a small patch in another part of the sky in the Hadean, larger than today's at 66 Ma. Galaxies beyond the Local Group were nearer by the cosmic scale factor. The nebulae are young: each is drawn only within its age, so the Orion Nebula is absent at 1.78 Ma, and none of today's shine at 66 Ma or before, when others, unknowable, did.

7.4 Events on their dates

The timeline also holds the sky's own dated events, which come on their days in whichever epoch's sky holds that day, and which the date picker lists under Extended events: every supernova, nova and stellar eruption known to have shone brighter than magnitude 3 (Table 8),

the 24 real comets at their best apparitions, three volcanic veils, three great aurorae, three meteor storms and three impacts, and three events to come. None is an epoch of its own: each is laid over the sky of its time, the volcanic veils on its air, the rest among its stars, meteors and aurorae. Going to one sets the clock to the hour it shows best, highest in the darkest sky (a meteor storm at its peak, a volcanic veil at dusk, an impact as it comes in), and the latitude it is best seen from: of the equator and the two mid-latitudes, where most people live, the one that sees it highest in the darkest sky, and a polar one only when none of those sees it 10° up at night.

7.5 Supernovae, novae and eruptions

Every supernova, nova and stellar eruption known to have outshone magnitude 3 appears on its date (Table 8): the supernovae of history from SN 185 to SN 1987A; those before history, dated by their remnants and pulsars, from a hypothetical one about 20 pc away at the end of the Devonian, 359 Ma, which may have stripped the ozone layer (Fields et al. 2020), through the two whose iron-60 lies in the deep-sea crust (Wallner et al. 2016; Breitschwerdt et al. 2016), to Vela Jr's a few thousand years ago; fifteen classical novae from 1848 to 1999 (Duerbeck 1987; Strope, Schaefer & Henden 2010); and three eruptions: P Cygni's of 1600 (de Groot 1969), CK Vulpeculae's of 1670, perhaps two stars merging (Shara, Moffat & Webbink 1985; Kamiński et al. 2015), and η Carinae's Great Eruption, second only to Sirius in 1843 (Smith & Frew 2011). A record's date is the day it was first seen, converted from the Julian calendar; one before history has a day chosen in the year its remnant's or pulsar's age gives, and where its place in the sky is not known it is assumed, as the table says. The remnants give the rest: SN 185's is RCW 86, a Type Ia's at 2.5 kpc (Williams et al. 2011), and SN 1181's Pa 30 (Ritter et al. 2021); the Monogem Ring is about 86,000 years old at 288 pc (Thorsett et al. 2003), the Cygnus Loop 10,000 to 20,000 at 735 pc (Fesen et al. 2018), the Vela pulsar 11,000 at 287 pc (Dodson et al. 2003), Puppis A 4,400 by its neutron star's motion at 1.3 kpc (Becker et al. 2012), and Vela Jr 2,400 to 5,100 at about 750 pc (Allen et al. 2015). The peaks are the records', or for a supernova without one a Type II-P's absolute magnitude, -16.75 (Richardson et al. 2014), at its remnant's distance: SN 1006 reached about -7.5 (Winkler, Gupta & Long 2003), Tycho's -4 (Krause et al. 2008). Each follows a light curve of its kind: a Type II-P's two weeks' rise, three months' plateau and radioactive tail (Anderson et al. 2014); a Type Ia's quicker rise and fall (Phillips 1993; Leibundgut 2000); a stripped star's Type Ib/c (Drott et al. 2011); a nova's rise of a day or two, its fall by two and three magnitudes in its own times and a power-law tail (Strope, Schaefer & Henden 2010), or the measured curve where it was odd, as RR Pictoris's slow rise and DQ Herculis's plunge into its own dust; and SN 1987A's slow climb to 2.9 (Hamuy & Suntzeff 1990). Each has a spectrum of its kind in the readout, P Cygni lines from a supernova's ejecta, broad Balmer and Fe II emission for a nova. The fainter are drawn as stars; the bright ones with a glare that grows from magnitude -2 to -9 , and the brightest shown lights the ground.

Two epochs are built round a supernova. Geminga's, about 342,000 years ago by its pulsar's spin-down age (Salvati & Sacco 2008), exploded 90 to 240 pc away toward Orion (Pellizza et al. 2005); a typical Type II-P peaks near absolute magnitude -16.75 (Richardson et al. 2014), so from 147 pc it reached about -11 , a fifth of the full Moon's light from a single point, bright enough to show by day and cast shadows at night for the three months of its plateau. Each follows a Type II-P light curve: two weeks' rise, the plateau, a drop of a few magnitudes after about 100 to 130 days, and the radioactive tail, fading a magnitude every hundred days, so it is gone to the eye in a few years. The ζ Ophiuchi supernova, 1.78 million years ago at 107 pc in the Scorpius–Centaurus association (Neuhäuser et al. 2020), unbound its companion, now the runaway star ζ Oph, and peaked near -11.6 , twice as bright. Its spectrum readout is a Type II-P near peak, with P Cygni profiles from fast ejecta (Filippenko 1997). At these distances neither touches the sky's colors (Thomas et al. 2016).



Figure 14: The Geminga supernova 342,000 years ago, near magnitude -11 in Orion, a fifth of the full Moon's light from a single point, among the stars moved back along their measured motions.

Three are to come. Betelgeuse's supernova is the same event as Geminga's, in the same patch of sky: 1.4° from Geminga's star in the sky of 342 ka, a red supergiant of 16.5 to 19 solar masses burning helium in its core, some 100,000 years from collapse, at 168 pc (Joyce et al. 2020), or 222 pc by radio astrometry (Harper et al. 2017). A red supergiant ends as a Type II-P, so it should peak at -10 to -10.6 , close to Geminga's -11 , and the Geminga sky is a fair picture of Orion's own to come; the site sets it, as an assumption, in AD 100,000. The others are tidal disruptions, stars torn apart by a black hole. The Large Magellanic Cloud's black hole, of about 6×10^5 solar masses by the hypervelocity stars it has thrown into the Milky Way's halo (Han et al. 2025), sits where Chisholm et al. (2026) predict; a Sun-like star's debris would fall back on it at about 140 times the Eddington rate, so the light holds near the Eddington luminosity, and at the Cloud's 49.6 kpc (Pietrzyński et al. 2019) it peaks near $V = -0.6$, as bright as Canopus for months, and stays visible for about thirty years. The rate is uncertain: with no nuclear star cluster the Cloud would see one in 10^5 to 10^6 years (Pfister et al. 2020), but it has thrown out about as many hypervelocity stars as the Milky Way's center, whose disruptions run near one in 10^4 ; at one in 33,000 years the median wait puts it in AD 25,000. Andromeda's black hole, 1.4×10^8 solar masses (Bender et al. 2005), can tear a Sun-like star apart only on a deep plunge round a fast spin, perhaps once in 10^5 to 10^6 years; the debris returns over about 300 days near the Eddington rate, and at 765 kpc it makes a first-magnitude star in M31's core for most of a year, visible for over a decade, set at the median wait in AD 210,000. Both are predictions, their dates assumed.

8 The night and what crosses it

8.1 Twilight and the night sky

Because the photometric scale of Section 2 is absolute, the night is drawn on the same scale as the day. The sky is computed for Sun heights down to 20° below the horizon, and past 9° below its zenith dims by about a magnitude per degree, as measured skies do, until the night sky's own light takes over near 18° . Without the Sun or Moon the sky has its own light: today $22.0 \text{ mag/arcsec}^2$ at a dark zenith (Leinert et al. 1998), half of it starlight and zodiacal light and half airglow, brighter toward the horizon.

Nearly all of today's airglow needs free oxygen: the 557.7 nm green and 630 nm red lines of oxygen atoms, the hydroxyl bands ($\text{H} + \text{O}_3$), the sodium D lines cycled through ozone, and the NO_2 continuum. We take its strength from the air's O_2 : 30% of today's at 1% of today's oxygen (2.2 Ga), where few atoms are left near 95 km, 80% at 10% (the Snowball and the Cryogenian, 169 DU of ozone), 90% at 81% (466 Ma), today's from today's level up, and log-linearly between, so it fades in through the Great Oxidation. Before it the oxygen airglow is gone, replaced by a faint violet glow of the O_2 Herzberg II bands from oxygen split off CO_2 , as on Venus (Krasnopolsky 1983): about as many photons as today's airglow but only 15% of its luminance, fading

out as O_2 rises from a ten-thousandth to a hundredth of today's. So Archean and Hadean nights were darker and bluer. These strengths are estimates; no model of an anoxic nightglow exists.

Starlight, the Milky Way and the airglow all come from above the air and are dimmed by it, at the rate given in Section 2, 1.086 times the air's optical depth at 550 nm: 0.24 magnitude per airmass in today's clean air, 0.18 to 0.21 in the clean, ozone-poor air of 3.8 to 0.7 Ga, 0.84 under the thick haze, 0.79 in a polluted city, 0.87 under the proto-Earth's guessed air and dust, 2.47 through the impact-winter soot, and 5.8 under 30 bar of CO_2 . That alone would leave the brightest stars at fourth magnitude overhead, but the bombardment's zodiacal glow, two thousand times today's, hides every one.

8.2 Noctilucent clouds

Noctilucent, or polar mesospheric, clouds are ice grains about 40–50 nm across (Baumgarten et al. 2008) near 83 km, at the summer polar mesopause, the coldest air on Earth. They form from late May to mid-August in the north, poleward of about 50° today, and show only in twilight with the Sun $6\text{--}16^\circ$ below the horizon, still sunlit against a dark sky. From 45° they are rare and low in the northern sky. From 75° the midsummer Sun never sets far enough to show them. The page does not place them: it draws a layer at 83 km and lets the twilight show it or not, as a web of fine filaments, long streaks along the wind crossed by shorter billows, in fields that come and go. Their light is computed through each epoch's air: the sunlight reaching the layer as it grazes past the Earth's shadow (little of it passing below about 19 km, where cloud and haze screen it, a height that varies from place to place and leaves the shadow's edge ragged), the grains' Mie scattering, and the path down to the eye. Ozone's Chappuis band takes the red from that grazing sunlight, which is most of why they look silvery blue (Lange et al. 2022). With no ozone, before 2.4 Ga, the same clouds would look white. In the hazy Archean, after Chicxulub and in the 30-bar Hadean, almost no sunlight reaches them. A bright display has an optical depth of about $1e-4$ (Fogle & Rees 1972), roughly a candela per square meter against a twilight sky a hundred times fainter. The page's twilight display curve would compress that contrast, so they are drawn, as the nebulae are, with a minimum step of brightness for each tenfold of light.

How often they come follows what they need: a cold mesopause, which more CO_2 cools further, and water there, most of it made from methane. Since industrialization methane has raised the water at their height by about 40%, which made them much brighter. They presumably existed earlier, but before the twentieth century the chance of seeing one was very small (Lübken et al. 2018). The first recognized sightings came in 1885, two years after Krakatoa, though one was recorded at Parma in 1840 (Bertolin & Domínguez-Castro 2020; Dalin et al. 2012). Two years is how long volcanic water takes to reach the summer mesopause (Wallis et al. 2025). Today a display comes on about a quarter of the season's nights at 60° . By 2100 they are brighter and reach farther toward the equator (Lübken et al. 2021; Lübken et al. 2024; Yu et al. 2023). Before the industrial era they are drawn faint and seldom. Deep time is uncertain and the page says so. In the high methane of the Cretaceous and Paleogene they spread to mid-latitudes (Dutta et al. 2024). The Archean's cold, ozone-free middle atmosphere and its methane may have made them common, and they are drawn so. In the Hadean, with the surface over 350 K, the upper air was warm and wet (Kasting et al. 2015), so none are drawn.

8.3 Aurorae

The aurora is an oval round the magnetic pole, fixed relative to the Sun: on a moderately active night today (Kp 3) it spans about $63\text{--}72^\circ$ latitude on the night side (the ovals of Feldstein & Starkov 1967). Its field lines reach out to the magnetopause, whose distance goes as the sixth root of the field's pressure over the solar wind's. At 3.45 Ga a field half to 70% of today's and the young Sun's dense wind held the magnetopause at about half today's distance (Tarduno et al. 2010),

Table 8: The supernovae, novae and stellar eruptions that outshone magnitude 3, and the events to come, in time order, as the site lists them under Extended events (*transients.js*). Dates are Gregorian, converted from the Julian records; the prehistoric ones are given by their age, and the future ones by an assumed year. Peaks are as seen from the Earth, from the records or from a Type II-P's absolute magnitude at the remnant's distance. The real comets, volcanic veils, great aurorae, meteor storms and impacts are listed with them on the site and described in their own sections.

Event	Date	Kind	Peak V	Note
A supernova at the end of the Devonian (?)	359 Ma	supernova	−15.2	Hypothetical: one at about 20 pc may have stripped the ozone layer at the end-Devonian extinction (Fields et al. 2020). Place invented.
An iron-60 supernova, 7 Ma	7 Ma	supernova	−11.75	Its iron-60 lies in the deep-sea crust (Wallner et al. 2016); about 100 pc away, place assumed.
An iron-60 supernova, 2.3 Ma	2.3 Ma	supernova	−12	One of the Scorpius–Centaurus supernovae whose iron-60 reached Earth (Breitschwerdt et al. 2016); about 90 pc away, place assumed.
The supernova that launched ζ Oph	1.78 Ma	supernova	−11.6	1.78 Ma, 107 pc away in Scorpius: it flung ζ Oph and a pulsar apart (Neuhäuser et al. 2020).
Geminga's supernova	342 ka	supernova	−10.9	342 ka, about 147 pc away in Orion; it left the Geminga pulsar (Pellizza et al. 2005).
The Monogem Ring supernova	86 ka	supernova	−9.5	About 86 ka and 288 pc away in Gemini; its remnant, the Monogem Ring, spans 25° of sky.
The Cygnus Loop supernova	15 ka	supernova	−7	10,000 to 20,000 years ago, 735 pc away; the Veil Nebula is its shell. Date assumed.
The Vela supernova	11 ka	supernova	−9.5	About 11,000 years ago, 287 pc away; it left the Vela pulsar. Date assumed.
The Puppis A supernova	4.4 ka	supernova	−4.5	About 4,400 years ago, 1.3 kpc away behind the Vela remnant. Date assumed.
The Vela Jr supernova	3.7 ka	supernova	−6	2,400 to 5,100 years ago, about 750 pc away; age and distance uncertain. Date assumed.
SN 185	6 Dec 185	supernova	−6	Recorded by Han astronomers in Centaurus; seen for eight months.
SN 386 (?)	16 Apr 386	supernova	0	A guest star in Sagittarius for three months; its remnant is uncertain.
SN 393 (?)	2 Mar 393	supernova	−1	A guest star in the tail of Scorpius for eight months; perhaps RX J1713.7–3946.
SN 1006	6 May 1006	supernova	−7.5	The brightest star in recorded history, low in Lupus; seen for about three years.
SN 1054 (the Crab)	10 Jul 1054	supernova	−6	Song astronomers saw it by day for 23 days, in Taurus; it left the Crab Nebula and its pulsar.
SN 1181	13 Aug 1181	supernova	0	Recorded in China and Japan in Cassiopeia for six months; its remnant is Pa 30.
Tycho's supernova (SN 1572)	16 Nov 1572	supernova	−4	In Cassiopeia, as bright as Venus; Tycho Brahe's measures showed it lay beyond the Moon.
P Cygni (1600)	18 Aug 1600	eruption	3	A luminous blue variable's eruption: a new third-magnitude star in Cygnus for six years.
Kepler's supernova (SN 1604)	9 Oct 1604	supernova	−2.5	In Ophiuchus, beside Jupiter and Saturn; the last supernova seen in our galaxy.
CK Vul (Nova Vulpeculae 1670)	20 Jun 1670	eruption	2.6	Seen by Anhelme and Hevelius, three times over two years; perhaps two stars merging.
η Carinae's Great Eruption	14 Mar 1843	eruption	−0.8	Ten solar masses thrown off in two decades; at its peak second only to Sirius.
V841 Oph (Nova Ophiuchi 1848)	27 Apr 1848	nova	2	Found by J. R. Hind at 5.6, well after a peak that may have reached 2.
T CrB (1866)	12 May 1866	nova	2	The Blaze Star's first recorded eruption, found by John Birmingham; a recurrent nova.
Q Cyg (Nova Cygni 1876)	24 Nov 1876	nova	3	Found by Julius Schmidt at Athens.
GK Per (Nova Persei 1901)	21 Feb 1901	nova	0.2	Found by Thomas Anderson in Edinburgh; its light echo was the first seen.
V603 Aql (Nova Aquilae 1918)	8 Jun 1918	nova	−0.5	The brightest nova since Kepler's supernova, outshone only by Sirius.
V476 Cyg (Nova Cygni 1920)	20 Aug 1920	nova	2	Found by W. F. Denning.
RR Pic (Nova Pictoris 1925)	25 May 1925	nova	1.2	Found by Hendrik Watson in South Africa; a slow nova, at its brightest two weeks later.
DQ Her (Nova Herculis 1934)	13 Dec 1934	nova	1.4	Found by J. P. M. Prentice; in April 1935 the dust it made hid it.
CP Lac (Nova Lacertae 1936)	18 Jun 1936	nova	2.1	Found by Kazuaki Gomi in Tokyo.
CP Pup (Nova Puppis 1942)	8 Nov 1942	nova	0.3	Found by Bernhard Dawson in Argentina; one of the fastest and brightest.
T CrB (1946)	9 Feb 1946	nova	3	The Blaze Star's second recorded eruption, eighty years after the first.
V446 Her (Nova Herculis 1960)	7 Mar 1960	nova	2.8	Found by Olaf Hassel, three days past its peak.
V533 Her (Nova Herculis 1963)	6 Feb 1963	nova	3	Found by Leslie Peltier and Elis Dahlgren, after its peak.
V1500 Cyg (Nova Cygni 1975)	29 Aug 1975	nova	1.7	The fastest bright nova known: it faded three magnitudes in four days.
SN 1987A	24 Feb 1987	supernova	2.9	In the Large Magellanic Cloud, 51 kpc away; its neutrinos reached Earth hours before its light.
V382 Vel (Nova Velorum 1999)	22 May 1999	nova	2.6	Found by Peter Williams in Australia.
A star torn apart by the LMC's black hole	AD 25,000	tidal disruption	−0.6	Predicted: a $6 \times 10^5 M_{\odot}$ black hole in the Large Magellanic Cloud disrupting a star, as bright as Canopus for months and visible for decades. Year and day assumed.
Betelgeuse's supernova	AD 100,000	supernova	−10.6	Due within about 100,000 years, 168 pc away; the year is assumed.
A star torn apart by Andromeda's black hole	AD 210,000	tidal disruption	1	Predicted: M31's $1.4 \times 10^6 M_{\odot}$ black hole tearing apart a star on a deep plunge, a first-magnitude star in Andromeda's core for most of a year, visible for over a decade. Year and day assumed.

which brings the oval's edge down to about 50° even in quiet times, and the young Sun's frequent flares and mass ejections (Airapetian et al. 2016) make storms the usual state. Through the Proterozoic the wind weakens (Wood et al. 2005) and the oval retreats toward the pole.

The colors follow the air. Today's green and red lines are oxygen atoms. At 2.2 Ga they are about a third of today's. With no free oxygen the aurora is nitrogen's: violet N_2^+ bands and a pink border of N_2 first positive bands where faster electrons reach lowest, brighter without oxygen to quench them, with a weak green line from CO_2 split by the electrons, as Perseverance saw on Mars (Knutsen et al. 2025). The 30-bar Hadean air is mostly CO_2 , so there the green line would be stronger and the nitrogen faint, but the air, at 5.8 magnitudes of extinction per airmass, and the bombardment's zodiacal glow hide the aurora altogether. Brightness is for a dark-adapted eye, which sees violet far better than the deep red. The ancient line strengths are estimates.

Each night has its own activity about the epoch's typical level, and the oval is drawn at it. Today that is Kp 3; the young Sun's typical night is far stormier, Kp 6 at 4.0 Ga, and its oval reaches correspondingly lower, to about 37° on the night side at 4.0 Ga and 43° at 3.8 Ga (Table 9 gives both). The arcs are thin sheets along the field lines, green below and red above, with field-aligned rays converging overhead on the magnetic zenith; they fold, drift and break up in two substorms a night near midnight. A storm of the class of September 1859, when aurora stood overhead near 40° magnetic latitude, brings today's oval down to about 45° and the young Earth's to the equator. Three great storms on record come on their dates in the modern-era skies, each drawn as that class of storm: the Carrington storms of late August and early September 1859, with aurora overhead in the Caribbean

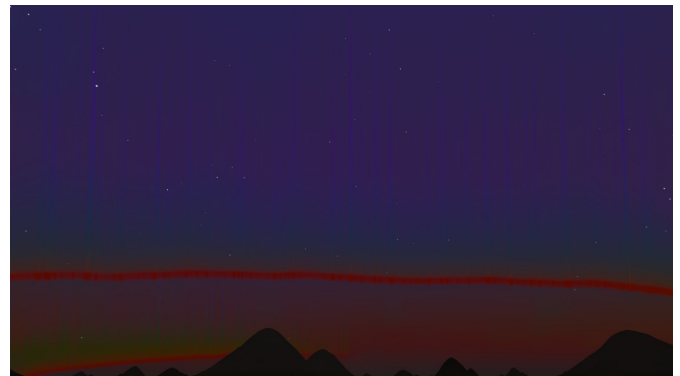


Figure 15: An aurora over the young Earth at 3.8 Ga, from mid-latitudes, on an active night, drawn as a dark-adapted eye sees it: with no free oxygen, nitrogen's violet bands and pink lower border rather than today's green and red. The aurora is brightened for print, 100 times its luminance on the site, where a true night is too dim to reproduce on paper.

(Green & Boardsen 2006); the storm of 13 to 15 May 1921, seen to Samoa and Jamaica (Silverman & Cliver 2001); and the storm of 10 and 11 May 2024, red aurora over Mexico and Florida, the strongest since 2003 (Hayakawa et al. 2025).

8.4 Meteors and meteor showers

Each meteor is a meteoroid entering the air along a straight path 80 to 125 km up, with its brightness, size and speed tied by the photographic relation of Jacchia, Verniani & Briggs (1967) and its count set by the measured fireball rate. Today a dark site sees about 8 an hour, more before dawn. A meteor shows only when brighter

than the sky around it, so twilight, moonlight and city light thin them out. The air enters three ways. Bright, fast meteors leave persistent trains that glow green and then orange; that chemistry needs oxygen and ozone, so there are no trains before the Great Oxidation. Each meteor's color comes from a spectrum built for its speed and the epoch's air: the metals of the meteoroid, a hotter component that grows with speed, and the air's own emission, oxygen and nitrogen today or carbon monoxide bands in a CO₂-rich air, which no one has measured. And in the Early Hadean's 30 bar every density level sits higher, so meteors burn about 22 km higher up.

The rate follows the lunar cratering record (Neukum et al. 2001): about 10,000 times today's at 4.5 Ga, extrapolated past the record's oldest ages, in the giant impact's debris, 500 at 4.0 Ga and 120 at 3.8 Ga, of slow, yellow-orange fireballs from a main-belt-like population (Strom et al. 2015; Marchi et al. 2014), with impact flashes on the closer Moon's dark side; twice today's at 2.7 Ga; and a hundred times today's fireballs at 466 Ma, after the L-chondrite parent body broke up (Schmitz et al. 2019).

Meteor showers come on their own dates. The modern-era skies have the 38 showers of the IMO's working list, apart from its Antihelion source (Rendtel 2027, Table 5), with their radiant and drift, speeds, population indices and peak rates, rising and falling about the maximum as Jenniskens (1994) measured them, and their outbursts and storms at the hour they were seen: the Leonids of 1799 to 2002, the Andromedids of 1872 and 1885, the Draconids of 1933 and 1946 and others (Jenniskens 1995 and the IMO's analyses), with the Leonid peaks predicted for 2034; the Leonid storm of 1833 and the Andromedid storms of 1872 and 1885 are among the extended events, at their peaks and from the latitude where the radiant stands highest in the dark. Today's streams are kept for 3,000 years either side of 2000. Showers last thousands of years, so further off, and in the older epochs, the sky has its own, drawn at random with the geometry, speeds and profiles of today's, a new set every 20,000 years, and outbursts at today's rate, about 0.5 a year above ZHR 100 and one in 45 years above 10,000. We take their number to follow the comets that feed them: three quarters from short-period comets, a quarter from long-period ones (only about a fifth of known streams have an identified parent; Ye & Jenniskens 2024), giving about 30 times today's at 4.5 Ga, 5 at 4.0 Ga, today's by 2 Ga and 1.75 at 1.78 Ma, in the comet shower after a star's passage; between the epochs they run geometrically, as the bombardment's decline does. No published work estimates showers in the early Solar System, so these are estimates, and in the bombardment they hardly show against the sporadic rate.

8.5 Fireballs and impacts

The largest meteoroids do not burn up. Bodies a meter across and more come in as superbolides, brighter than magnitude -15 , and leave dust trails from about 80 km down to where they break up at 25 to 40 km, which drift and shear in the high winds, as Chelyabinsk's did for over an hour (Borovička et al. 2013); today about one comes within 1,100 km of a given place every three years, and in the bombardment several an hour. Bodies brighter than about -24 reach the ground. When one strikes within 200 km it is drawn with its fireball, a thermal pulse cooling from 6,500 to 2,000 K, the blast wave, a condensation ring and the rising cloud, scaled from nuclear-test and impact-effect relations (Glasstone & Dolan 1977; Collins, Melosh & Marcus 2005). Today that happens to a given place about once in 50,000 years; in the bombardment, constantly. In the bombardment epochs, impact flashes also show on the closer Moon's night side, at today's measured rate scaled up (Suggs et al. 2014).

Three impacts on record come on their dates, each a meteor with its energy, speed and path, striking or bursting near the observer: Tunguska, 30 June 1908, about 12 megatons at 15 km/s entering at 35° (Chyba, Thomas & Zahnle 1993; Longo 2007), seen from 65 km as from Vanavara's trading post; Chelyabinsk, 15 February 2013, half a megaton at 19.2 km/s entering at 18° (Popova et al.

2013), bursting 30 km up 40 km away; and Chicxulub, 66 Ma, a carbonaceous asteroid (Kyte 1998) 10 km across at 20 km/s, entering steeply, at about 60° from the north-east (Collins et al. 2020), seen from 200 km. An airburst brightens down into the thicker air, flares as it bursts, Chelyabinsk to about -25 , and leaves a glowing cloud that fades by about four magnitudes a second. Chicxulub's hour is assumed, in the evening twilight with the Sun 9° down, so that the asteroid, coming from the north-east, is lit nearly full face against a darkening sky and stays sunlit until it meets the air: by the H, G magnitude system for its size and an albedo of 0.05 it shows as a star some 40 minutes before it strikes, and in its last seconds as a cratered, lumpy disk 1.5° across, drawn with Phobos's map and shape standing in for a face no one knows. In the air its meteor is the glowing shocked air about it, brightening with the air's density from about the Sun's brightness at 100 km to its full light at the ground, where it strikes in a single flash; the fireball, the rising cloud and the condensation dome are drawn to fit their distance rather than at the thousands of kilometers the scalings give. Played faster than real time, the clock slows to real time 30 seconds before each, so the fall is seen at its own pace.

8.6 Dust, comets and the Ordovician ring

The zodiacal light, sunlight off interplanetary dust, is part of today's natural night sky. Where the inner Solar System held more dust the excess is drawn along the ecliptic, with the gegenschein opposite the Sun: 30 times today's after the L-chondrite break-up and 50 to 2,000 times during the bombardment (estimates after Nesvorný et al. 2010), as bright as a moonlit sky, hiding the fainter stars and meteors. At 466 Ma the speculative debris ring of Tomkins, Martin & Cawood (2024) is drawn between 1.55 and 2.75 Earth radii with a normal optical depth of at most 0.00015: lost in the blue by day, a low arch at night cut by the Earth's shadow, and at the equator a source of slow, grazing fireballs from the west. The break-up's dust rises over 50,000 years from 466.1 Ma, holds for two million years and decays with a one-million-year e-folding time, and the meteors with it; the ring, if there was one, decays over tens of millions of years (a 20 Myr e-folding time here). Between the epochs the zodiacal light and the meteor and comet rates run geometrically, as the bombardment declined.

Comets in the modern-era skies are the real ones on their real dates, from JPL's orbits, for the perihelia on record, 1577 to 2127, and Halley's back to its passage of 837 (Yeomans & Kiang 1981), its node and perihelion turned 1.22° and 1.04° a century so that the 837 passage comes 0.033 AU from Earth on 10 April (Julian), as recorded, with a tail of some 50° at magnitude -3.4 . The periodic ones also return every orbital period beyond the perihelia on record, Swift-Tuttle's in 1596 and 1729 and Pons-Brooks's four times from 1599 to 1812. Each of the 24 is listed among the extended events at the apparition where it stood out most, on the day it was brightest against the faintest star that shows at its angle from the Sun, so a comet at perihelion behind the Sun waits for its evenings. Elsewhere comets are drawn at the rate of their time, about one naked-eye comet a year today, 30 times that at 4.5 Ga while the giant planets eroded and then scattered the comet disk, falling to today's level by about 2 Ga, and about half of today's in the quiet Phanerozoic epochs, because the present flux of new long-period comets is still about two to two and a half times the tide-only rate (Kaib & Raymond 2026). After the ζ Ophiuchi star's passage the rate swells to about four times today's at 1.78 Ma and dies away over a million years or so, a comet shower. Their heads and tails are dimmed by each epoch's air like the stars.



Figure 16: The proto-Earth's bombardment, at 4.55 Ga, from mid-latitudes, on a moonless world. Left: the whole sky at one instant of a midnight on the site's fisheye dome (zenith in the middle, horizon at the rim, north up), with about 18 meteors in the air at once, at 30,000 times today's rate, most of them slow asteroidal fireballs. Right: a ground strike in the first-person view, 6.8 seconds into an 8.5-second fall at 13.5 km/s: a stony body about 120 m across, magnitude -26.4 , about as bright as the Sun, coming down 110 km away with 70 megatons, its dust trail behind it, and its light filling the night sky with the Sun 22° below the horizon. The weather's clouds are taken away for this view; the dust trail is drawn by the same cloud pass.

Table 9: Other phenomena by epoch. Refraction is the horizon bending relative to today's, from the epoch's gases. The starlight's extinction is 1.086 times the air's optical depth at 550 nm. Airglow and aurora strengths are estimates; the aurora's latitude is the night-side equatorward edge of the oval, from the magnetopause distance, at Kp 3 and at the epoch's typical activity. Meteor and zodiacal-light rates are relative to today's.

Epoch	Refraction	Airglow	Starlight extinction (mag/airmass)	Aurora	Meteors	Zodiacal light
4.55 Ga proto-Earth	$5.7 \times$ (trapped)	violet CO ₂ glow only	0.87	from 35° (Kp 3), the equator (Kp 7); green CO ₂ line, faint N ₂	$30,000 \times$	$10 \times$
4.5 Ga Hadean	$47 \times$ (trapped)	violet CO ₂ glow only	5.8; no stars in the zodiacal glow	hidden by the air	$10,000 \times$	$2,000 \times$
4.0 Ga Hadean	$1.8 \times$	violet CO ₂ glow only	0.37	from 48° (Kp 3), 37° (Kp 6); violet and pink N ₂	$500 \times$	$300 \times$
3.8 Ga Archean	$0.97 \times$	violet CO ₂ glow only	0.20	from 51° (Kp 3), 43° (Kp 5.5); violet and pink N ₂	$120 \times$	$50 \times$
2.7–2.52 Ga Neoproterozoic	$0.90 \times$	violet CO ₂ glow only	0.19 clear, 0.35–1.8 with the haze	from 55° (Kp 3), 49° (Kp 5); violet and pink N ₂	$2 \times$	$1.5 \times$
2.2 Ga post-GOE	$0.85 \times$	oxygen lines at 30%	0.21	from 60° (Kp 3), 58° (Kp 4); O lines at a third	$1.3 \times$	today
700 Ma Snowball	$0.83 \times$	oxygen lines at 80%	0.18	from 63° (Kp 3), 62° (Kp 3.3); O lines at 80%	$0.6 \times$	today
650 Ma Cryogenian	$0.83 \times$	oxygen lines at 80%	0.22	from 63° (Kp 3), 62° (Kp 3.3); O lines at 80%	$0.6 \times$	today
466 Ma Ordovician	$0.97 \times$	oxygen lines at 90%	0.25	today's	$100 \times$ fireballs	$30 \times$
300 Ma Carboniferous	$1.11 \times$	today's	0.31	today's	$0.5 \times$	today
66 Ma impact winter	$1.0 \times$	today's, dimmed by soot	2.47	today's	today	today
1816 volcanic year	$1.0 \times$	today's	0.68	today's	today	today
Today	$1.0 \times$ ($34'$ at the horizon)	$22.0 \text{ mag/arcsec}^2$ natural sky	0.24	$63\text{--}72^\circ$ at Kp 3; O green and red	8 an hour	—

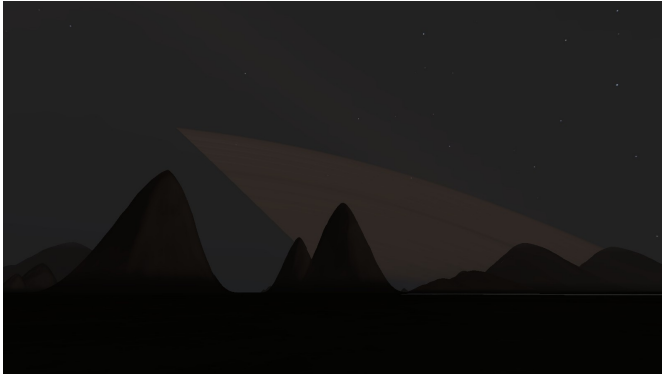


Figure 17: The night at 466 Ma, after the L-chondrite parent body's break-up: a hundred times today's fireballs, a bright zodiacal band, and the speculative ring of [Tomkins, Martin & Cawood \(2024\)](#) as a faint arch.

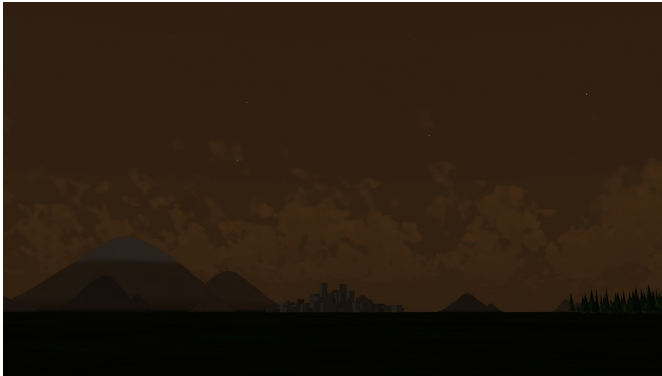


Figure 18: A city night today, looking toward the city 2.8 km away, its towers along the horizon: sodium and LED glow at $18.8 \text{ mag/arcsec}^2$ hides all but the brightest stars.

9 The sky people made

9.1 City light

In the modern epochs the observer stands in a mid-sized city: a zenith glow of $18.8 \text{ mag/arcsec}^2$ today ([Falchi et al. 2016](#)), 1.6 times today's in polluted air, and held at today's level in 2100 (the recent 9.6% a year, [Kyba et al. 2023](#), cannot be projected that far). Back in time the glow follows the growth of electric light: only lamplight until 1900, then growing about 3% a year, an e-folding time of 30 years, between the 2.2% a year that satellites saw in lit area and radiance in 2012–2016 ([Kyba et al. 2017](#)) and the 9.6% a year in sky brightness that observers reported in 2011–2022. That reaches a third of today's in 1990, near the first World Atlas ([Cinzano, Falchi & Elvidge 2001](#)), and today's now. Its color goes from gas and incandescent light to orange sodium by 1990 and on to today's LEDs. The glow rises about threefold toward the horizon, and cloud bases over the city glow orange several times brighter than the clear sky ([Kyba et al. 2011](#)). Against that glow the city keeps only the brightest stars, and none of the Milky Way.

9.2 The sky before electric light

The volcanic year's towns burn oil lamps and candles: Britain then used about one six-thousand-five-hundredth of the artificial light per head that it used in 2000 ([Fouquet & Pearson 2006](#)), so the town's glow on the sky is some ten thousand times fainter than a modern city's, and the Milky Way stands over the rooftops. The 1900 epoch, the dark nights, keeps that lamplight from the Pleistocene up to 1900, and the city of the later skies is only there once its glow has grown (*City light*).

9.3 Aircraft

The modern-era skies have airliners and their contrails: about 1.1 aircraft over each $10,000 \text{ km}^2$ of busy mid-latitude sky by day, from



Figure 19: A night in July 1815 under Tambora's young veil, among volcanic peaks with glowing summits: the towns' oil lamps barely touch the sky, and the Milky Way shows faintly above the peaks.

European traffic statistics, at 9 to 12 km along a few airways, quieter after midnight; under half of today's traffic in 1990, twice today's in 2100, none in 1816 or 1900. A contrail forms where the exhaust's mixing line crosses saturation ([Schmidt 1941](#); [Appleman 1953](#)), most often at mid and high latitudes, and lives seconds in dry air but spreads into contrail cirrus lasting hours in the 10 to 20% of cruise levels that are supersaturated with respect to ice ([Gierens et al. 1999](#); [Schumann 2005](#); [Minnis et al. 1998](#)). At night the aircraft show as their navigation lights, beacon and strobes.

9.4 Satellites

From Sputnik on, the skies dated 1957 and later carry the satellites in orbit on their date. [Lawler, Boley & Rein \(2022\)](#) put every filed mega-constellation on orbit, 65,262 satellites in 30 shells from 328 to 1,200 km, and found the worst naked-eye light pollution near 50° latitude; we let these fill by 2040, and they are the 2100 sky's. Before that each fills as it was launched: Starlink from 2019 (its second generation as it flies today, near 530 km), OneWeb, Kuiper and Guowang, over some 4,000 satellites and spent stages of every other program in the orbits they use, from one in 1957 to 2,200 by 1990. The ISS flies its real orbit, from its element set of October 2026, and its shape grows as it was assembled, from its first module in 1998 to its planned deorbiting at the end of 2030; Mir flies an orbit of its kind from 1986 to 2001. The page has no longitude, only sundial time, so a pass is the one seen at that hour somewhere on the observer's latitude.

Each satellite has a simple shape after its real design, a bus and its solar wings and, on the larger, radiators, modules and a truss, drawn when the zoom resolves it, and its brightness is that shape's. Each face is lit by the Sun and by the sunlit Earth below, each patch of ground by its own Sun's height, so that near the terminator only the lit crescent toward the Sun counts; the cells lie under cover glass and radiators are mirror-like optical solar reflectors, so besides their diffuse light they glint, and mirror the Earth; the wings follow the Sun on their drive, about 2° off where it aims them, and the ISS's on two axes as its rotary joints turn them. Starlinks fly SpaceX's brightness mitigation, their wings edge-on to the Sun over observers in twilight or darkness, with the first generation's buses under visors and the second's under mirror film; so, the second generation comes out about as bright as Lawler, Boley & Rein's diffuse sphere of 0.8 m^2 , which matched the Starlinks seen in 2020 and 2021, and the first a little fainter. The reflectances are estimates, as no operator publishes its own, and the Sun stands where it does on the date. At 45° an hour after sunset on the March equinox, three satellites are brighter than sixth magnitude in 1965, about twenty in 1990 and about ninety today, a few hundred in 2100; the ISS passes at magnitude -1 to -2 some 800 km off.

On top of the 2100 fleet are the orbital datacenters modeled by [Boley, Lawler & Rein \(2026\)](#). Of their three filed designs we take Blue Origin's Sunrise and the relaxed one of their two node spreads: 51,600 Sun-synchronous satellites from 500 to 1,800 km in a dawn–dusk cross of rings whose nodes wander 10° to either side of the terminator. The



Figure 20: Dusk in 2100: the filed megaconstellations and the Sunrise orbital datacenters, still in sunlight above the darkening sky.

paper gives each satellite 800 m^2 , panels, radiators and bus together, the size it calls conservative next to designs several times larger, and treats it as a diffuse sphere at albedo 0.2, a deliberately simple reference. We draw a satellite instead, after the designs proposed for such craft (Starcloud's, and Google's Project Suncatcher): two solar wings of 800 m^2 in all on a drive along the orbit, which follow the Sun but for its share along the orbit, $10\text{--}25^\circ$ with the season; mirror-like radiators; a flat bus. At 45° on the March equinox, an hour after sunset, some 1,600 are brighter than fifth magnitude and 370 brighter than third, less than half as many as the sphere gives, in a band along the terminator, each crossing the dome in minutes; two and a half hours after sunset none is brighter than fifth. On the December solstice an hour after sunset some 4,800 are, until about 9 p.m., and the brightest are glints, the cover glass mirroring the Sun low in the east at dusk, as bright as magnitude -4 ; in June's short nights none is brighter than fifth magnitude.

10 Epoch by epoch

The panels that follow are laid out identically so they can be compared at a glance. Each begins with the epoch's name and a one-line summary of the atmosphere assumed (Table 2 gives the full parameters). The upper row shows the noon sky dome at three latitudes, the equator, a mid-latitude site and the summer pole, with the zenith at the top of each swatch and the horizon at the bottom, the correlated color temperatures of both, and the Sun's disk drawn in its own color at its noon elevation, with a brightness that reflects how much of it survives the atmosphere. The two strips beneath trace the sky from the solar horizon across the zenith to the antisolar horizon with the Sun on the horizon and 4° below it. All swatches are shown at a brightness relative to today's clean sky, so a dim epoch reads as dim. The paragraph after each panel describes that epoch's sky and what else was in it.

Proto-Earth, $\sim 4.55\text{ Ga}$

before the Moon-forming impact; a guessed air of $\sim 3\text{ bar CO}_2$ over 1 bar N_2 , with impact dust; the young Sun at 17 Myr

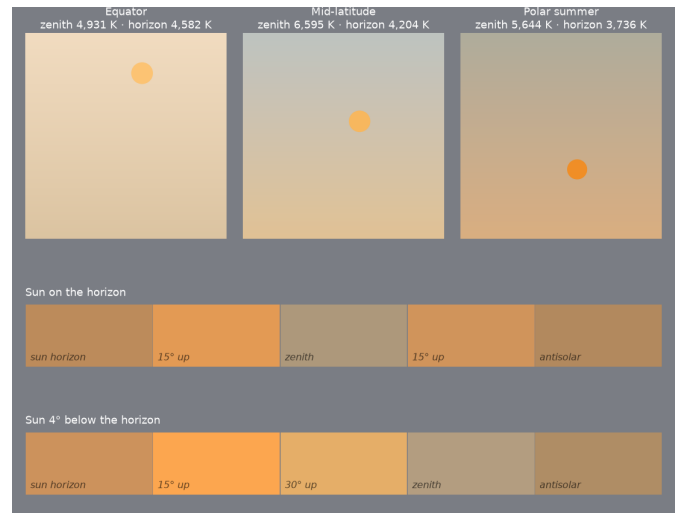


Figure 21: Proto-Earth, $\sim 4.55\text{ Ga}$. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

Some 17 million years after the first solids, the gas of the Sun's disk has just cleared, and with it, in the reading of the meteorites' bombardment ages (Edwards et al. 2024; Liu, Raymond & Jacobson 2022), the giant planets went unstable at about this time, some 5 to 20 million years after the first solids; we draw them just before it. Jupiter and Saturn sit in 3:2 resonance near 5.6 and 7.3 AU, and beyond them three ice giants: Uranus and Neptune, nearer than now, and between them and Saturn a fifth giant like Neptune, named here Oceanus, which Jupiter will throw out of the Solar System (Nesvorný 2011; Nesvorný & Morbidelli 2012). Neptune still has its own family of regular moons, named here Kymo, Galene, Thetis and Amphitrite; capturing Triton will scatter and destroy them (Rufu & Canup 2017). There is no Moon: the Earth is still growing, and Theia, the Mars-sized body that will strike it and make the Moon, is a wandering planet near the Earth's orbit, brighter than Venus when it passes close. Mercury still has most of its mantle, and Anteros, named here, the Mars-sized body that will graze it and then strike Venus, wanders between them; farther out Enyo, also named here, waits to make Mars's crustal dichotomy. The Sun is a pre-main-sequence star 17 million years old (Baraffe et al. 2015): 4,600 K, half today's light, a cooler, oranger disk 7% larger. Nothing constrains the proto-Earth's air; we take it as 3 bar of CO_2 over a bar of nitrogen, with dust from the impacts, so the sky can be seen through it. Where each planet was on any day cannot be known.

Early Hadean, ~4.50 Ga

~10 Myr after the Moon-forming impact: magma ocean frozen, ~30 bar CO₂ left; Moon at ~8 Earth radii

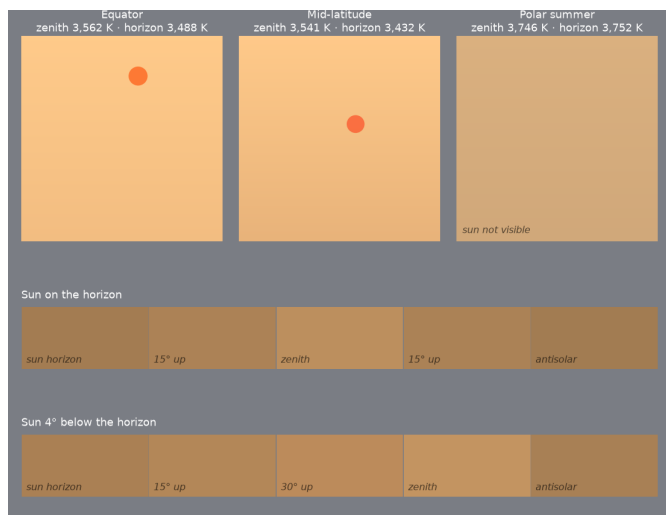


Figure 22: Early Hadean, ~4.50 Ga. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

About ten million years after the Moon-forming impact. The magma ocean has frozen, the steam of the impact has rained out into the first ocean, and tens of bars of CO₂ are left in the air, which we take as 30 bar. A ~30-bar CO₂ atmosphere has a Rayleigh optical depth near 5 at 550 nm and about 18 in the violet, so blue light is scattered back to space many times before it reaches the ground. What arrives is a diffuse, shadowless, peach-white glow of ~3,500 K, nearly identical from zenith to horizon, under a young Sun that is only 68% as bright. The Sun itself is a dim ember at the equator and vanishes entirely at mid and high latitudes: this is a Venus-like sky. Sunset is a brief, deep-orange dimming of the whole dome rather than an event at the horizon. Above it, the Moon is still only about 8 Earth radii away (Korenaga 2023): 4° across, seven and a half times its width today and 57 times its area, its own magma ocean still open, glowing orange through cracks in its crust, and going round the Earth in 32 hours in the plane of the equator, while the Earth turns in under 6. It crosses the sky in hours, and for weeks around each equinox it eclipses the Sun at every new Moon, somewhere on the Earth, and passes through the Earth's shadow, 14° across at its distance, at every full Moon. Tidal recession will carry it out to about 39 Earth radii by 4.4 Ga. We date the giant planets' instability to 4.48 Ga, the latest that the dated impact record allows (Mojzsis et al. 2019), so the fifth giant, Oceanus, and Neptune's first moons are still here; the bombardment ages favor an earlier one (Edwards et al. 2024), as in the 4.55 Ga sky. Through 30 bar of CO₂ and the glow of the impact's debris no star shows; the planets and their moons are there to be found by zooming in. The Sun is 67 million years old, near the main sequence: 5,500 K and 68% of today's light.

Late Hadean, ~4.0 Ga

CO₂ mostly drawn down into carbonate; ~1 bar N₂, ~0.5 bar CO₂

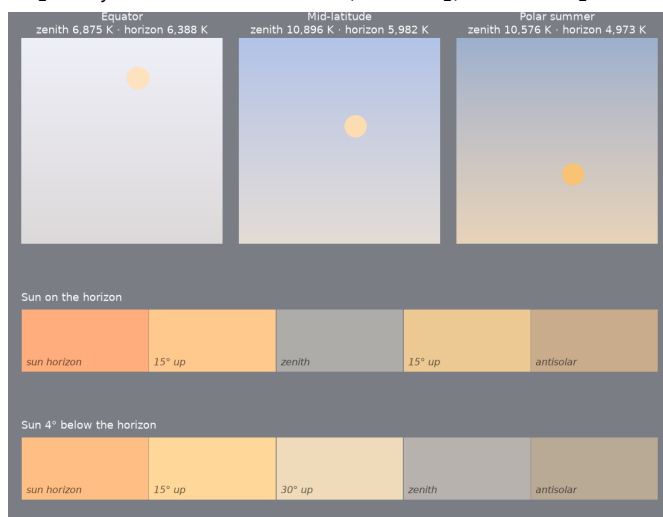


Figure 23: Late Hadean, ~4.0 Ga. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

Once most of the CO₂ has gone into carbonate, Rayleigh scattering falls to roughly twice the modern value. The sky turns pale blue at the zenith but clearly whiter than today (6,900–10,900 K versus 8,300–17,800 K), because the extra scattering fills the dome with multiply-scattered white light. Horizons are milky, and cream toward the poles. The setting Sun is deep red and the twilight zenith, with no ozone yet, is a pale gray rather than blue.

Early Archean, ~3.8 Ga

haze-free, anoxic; CO₂ ~0.1 bar, CH₄ ~1000 ppm, no ozone

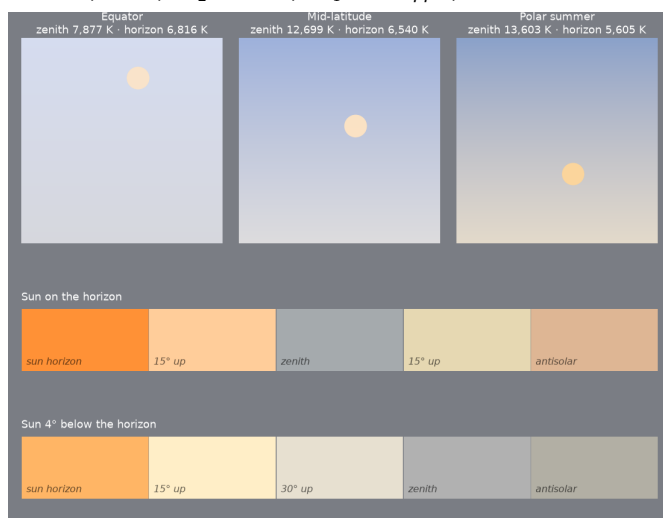


Figure 24: Early Archean, ~3.8 Ga. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

With CO₂ down to ~0.1 bar, noon skies are close to modern blue, only slightly whiter. The difference is at dusk. The blue of the modern twilight zenith is produced by ozone absorbing yellow-orange light (the Chappuis band) along the long grazing path; with no free O₂ there is no ozone, so the Archean twilight zenith is a pale gray, and the whole sky fades from blue to gray to orange as the Sun sets. Sunsets themselves are much like today's, slightly redder from the extra CO₂ and dimmer Sun.

Neoproterozoic, ~2.7 Ga (clear)

haze-free between haze episodes: $CH_4/CO_2 \sim 0.06$, below the ~ 0.1 at which haze forms

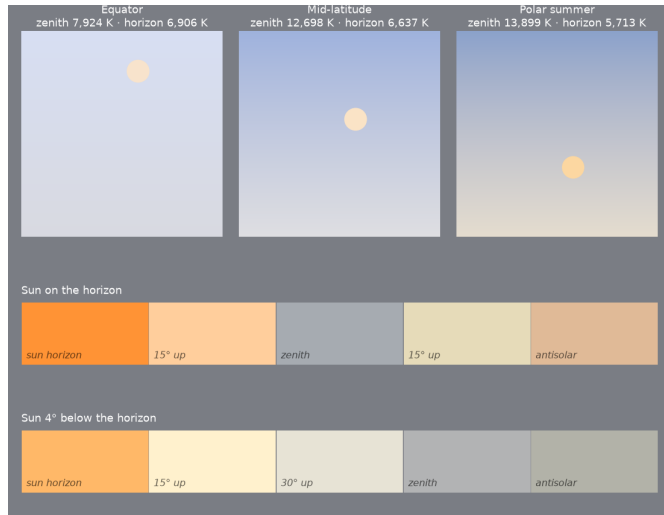


Figure 25: Neoproterozoic, ~2.7 Ga (clear). Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

For most of the Neoproterozoic the sky was clear. Sulfur and carbon isotopes from South Africa and Western Australia, 2.7 to 2.5 Ga, keep returning to the same haze-free background between episodes of haze (Zerkle et al. 2012; Izon et al. 2015): methane at a few hundredths of the CO_2 , short of the tenth at which an organic haze forms. With no ozone and a twentieth of a bar of CO_2 the noon sky is close to a modern blue, a little whiter, and the twilight zenith, with no ozone to color it, turns gray rather than blue as the Sun goes down.

Neoproterozoic haze episode, ~2.58 Ga (thin haze)

$CH_4/CO_2 \sim 0.2$: the stable thin organic haze of Zerkle et al. 2012, $\tau_{550} \sim 0.15$

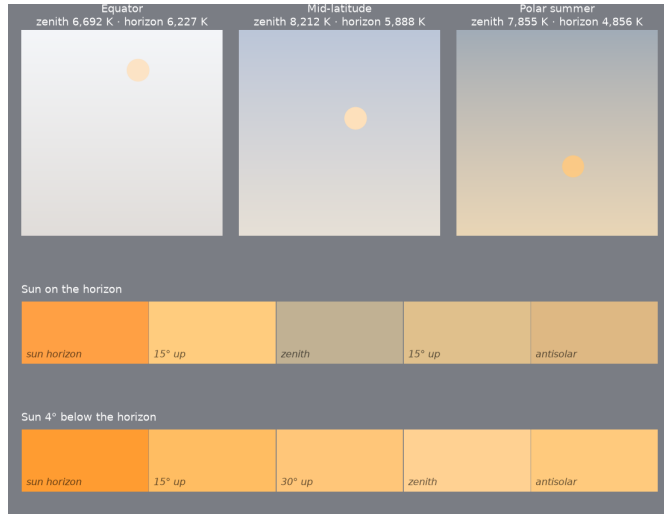


Figure 26: Neoproterozoic haze episode, ~2.58 Ga (thin haze). Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

One of the haze episodes the isotope records preserve: three in the 2.65–2.5 Ga Ghaap Group alone (Zerkle et al. 2012), here at about 2.63 and 2.58 Ga, each lasting about 1.4 million years and thickening over the first 0.3 (Izon et al. 2017). Once the biosphere pushed methane past a tenth of the CO_2 the haze shielded methane from its own destruction and ran on to a stable ~ 0.2 , where Zerkle et al.'s model holds it: an organic haze at optical depth ~ 0.15 . It pushes the zenith toward a pastel, milk-blue (6,700–8,200 K) and lays a warm cast on the horizon; at the poles, where sunlight crosses the haze obliquely, the horizon turns visibly cream. Twilight is orange all the way to the zenith.

Neoproterozoic haze episode, ~2.52 Ga (thick haze)

"Pale Orange Dot": Titan-like fractal organic haze, $\tau_{550} \sim 0.6$

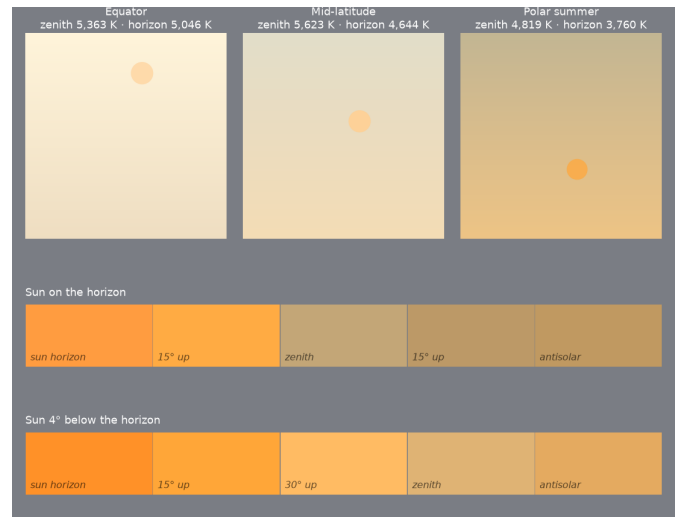


Figure 27: Neoproterozoic haze episode, ~2.52 Ga (thick haze). Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

The haze episode of about 2.52 Ga, the youngest in the Ghaap Group and the one Izon et al. (2017) resolved, is drawn at the thick end of what models allow. This is the "Pale Orange Dot" seen from below. At optical depth ~ 0.6 the haze absorbs blue and scatters forward, so the entire dome is a warm cream to pale tan ($\sim 5,400$ K at the equator, $\sim 4,800$ K at the poles) with little zenith-to-horizon gradient, the horizon only a little warmer: the sky looks like a bright overcast made of orange-tinted glass. The Sun is a soft, defined disk (haze scatters strongly forward) at 4,100 K. Sunsets are deep and long: the solar horizon reaches vermilion, the sky 15° above the Sun is amber, and the antisolar sky is peach rather than pink.

Neoproterozoic haze episode, ~2.52 Ga (very thick haze, upper bound)

the thick episode at the upper end of plausible haze, $\tau_{550} \sim 1.5$: $CH_4/CO_2 \sim 0.2$; in the report only

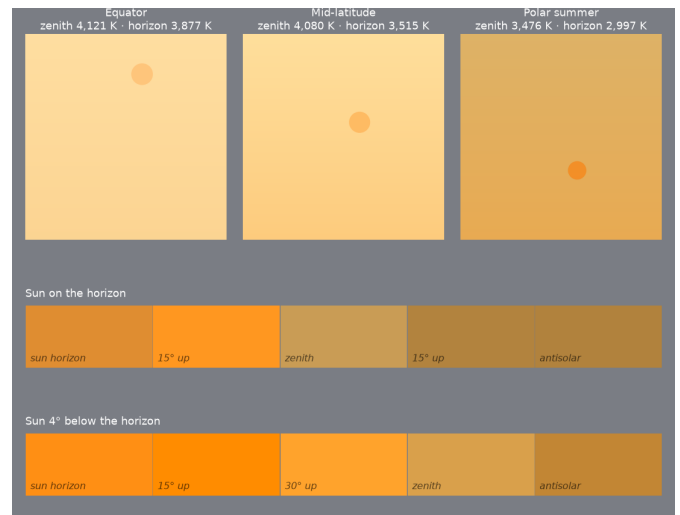


Figure 28: Neoproterozoic haze episode, ~2.52 Ga (very thick haze, upper bound). Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

At the upper end of plausible haze ($\tau \approx 1.5$) the sky is a uniform saturated apricot (3,000–4,100 K), as on Titan, and the polar Sun is reduced to an orange smear. The ground under it gets roughly 20–30% of a clear sky's sunlight.

Paleoproterozoic, ~2.2 Ga

after the Great Oxidation Event: $O_2 \sim 1\%$ PAL, ozone column 66 DU

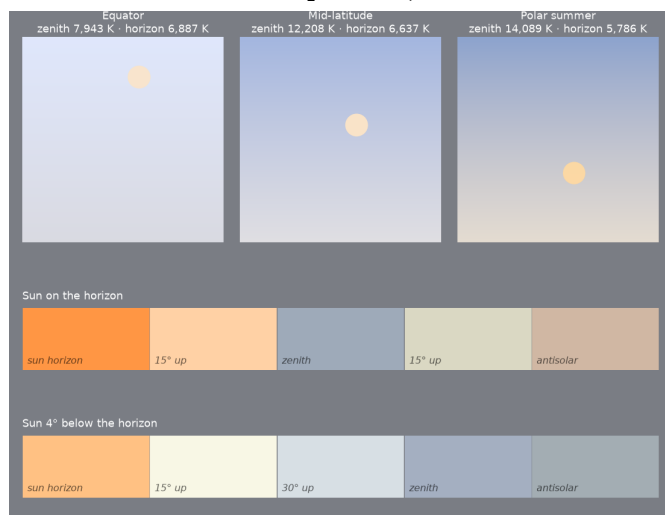


Figure 29: Paleoproterozoic, ~2.2 Ga. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

After the Great Oxidation Event, about 1% of today's O_2 builds an ozone column of 66 DU, the [Cooke et al. \(2022\)](#) global mean for that oxygen level: about a fifth of a modern mid-latitude column, not the half that older estimates gave. Noon skies are already modern blue. Twilight is where the thin column shows. With the Sun 4° below the horizon the zenith leaves the gray of an ozone-free dusk ($\sim 6,600$ K) and becomes a pale blue ($\sim 8,400$ K). It is not yet the deep blue of a 300 DU twilight ($\sim 24,000$ K). That saturated blue dusk is in place once the column is near modern, as in the snowball sky at 169 DU. (The pink antisolar arch needs no ozone: it is a Rayleigh effect and shows up faintly even in the Hadean model.)

Snowball Earth, ~700 Ma

the Sturtian glaciation, 717-661 Ma: cold, dry, very clean air over ice (albedo 0.75); ozone 169 DU

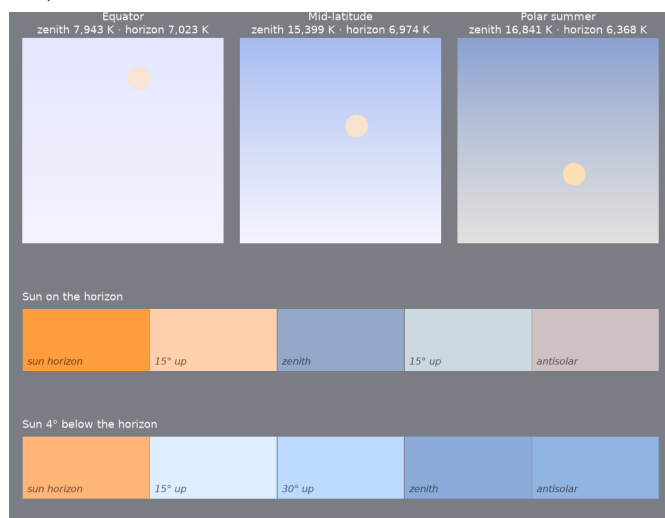


Figure 30: Snowball Earth, ~700 Ma. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

A frozen planet has dry, clean air and a surface albedo near 0.75, and together they give the bluest mid-latitude sky in Earth's history: 7,900 K at the equatorial zenith, 15,400 K at mid-latitudes and 16,800 K over polar ice. The sunlit ice lights the sky from below and deepens the zenith's blue, 15,400 K against 12,700 K for the same gases over the open sea of the Cryogenian, though the horizons whiten much as they do today. Sunsets are golden and comparatively pale; there is little aerosol to redden them. This is the Sturtian glaciation, from about 717 to 661 Ma; the Marinoan, about 639 to 635 Ma, is drawn the same.

Cryogenian, ~650 Ma (between the snowballs)

the open sea and bare land between the Sturtian and Marinoan glaciations: $O_2 \sim 10\%$ PAL, ozone 169 DU

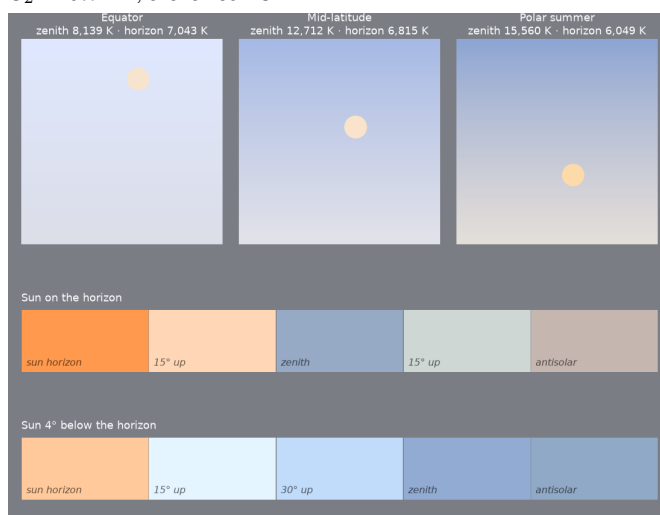


Figure 31: Cryogenian, ~650 Ma (between the snowballs). Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

Between the two snowballs: the 22 million years from the end of the Sturtian glaciation (661 Ma) to the start of the Marinoan (about 639 Ma). The gases are the snowball's, with oxygen at a tenth of today's and an ozone column of 169 DU, with more aerosol and no glacial dust, but the sea is open and the land bare, so the sky is a clean, slightly deep blue over a dark surface, and with the Sun 4° down the zenith is a paler blue than today's, about 13,300 K against 24,000, under the thinner ozone layer.

Ordovician meteor storm, ~466 Ma

after the L-chondrite parent body broke up: $O_2 \sim 17\%$, $CO_2 \sim 2,500$ ppm, a little meteoric dust aloft

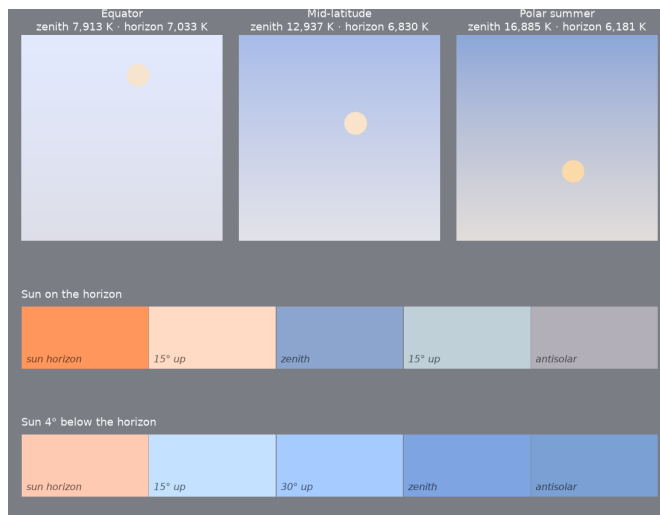


Figure 32: Ordovician meteor storm, ~466 Ma. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

About 466 million years ago the L-chondrite parent body, an asteroid about 150 km across, was shattered in the main belt, and its fragments still make up almost a third of the meteorites that fall today. For more than two million years the fine dust reaching Earth rose a thousandfold or more, and decimeter stones about a hundredfold: fossil meteorites lie scattered through Swedish limestones of that age, and the dust may have helped tip the climate toward the mid-Ordovician ice age ([Schmitz et al. 2019](#)). The meteors here come a hundred times as often as today, most of them slow and yellow with sodium, and we take the zodiacal light as thirty times today's, a glowing band along the ecliptic. The ring is speculation: all 21 known Ordovician craters lie within 30° of the paleo-equator, which led [Tomkins, Martin & Cawood](#)

(2024) to propose that a large fragment broke up inside the Roche limit into a ring that lasted tens of millions of years; it is drawn as a faint, sunlit band that Earth's shadow cuts at night, with its debris falling at the equator as slow fireballs from the west. The air itself is close to today's: about 17% oxygen, 2,500 ppm CO₂, an ozone layer within a few percent of the modern one, under a Sun 4% fainter, so the day sky is today's blue.

Carboniferous, ~300 Ma

O₂ ~30-35%; total pressure ~1.1 bar; wildfire smoke common

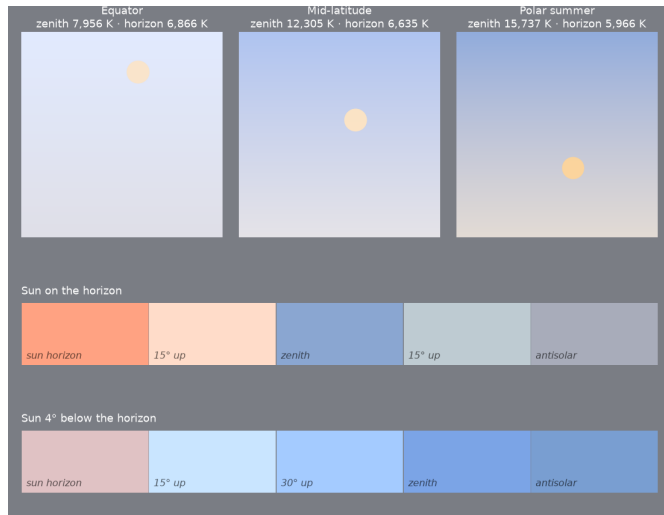


Figure 33: Carboniferous, ~300 Ma. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

Oxygen at 30–35% raises the total pressure and Rayleigh scattering by ~10%, so skies are marginally brighter and horizons a touch whiter than today. Frequent wildfire smoke in the high-O₂ world would have produced red suns and brown-orange horizons far more often than in the modern era.

Late Cretaceous, 66.1 Ma

clean air much like today's, before and after the impact winter

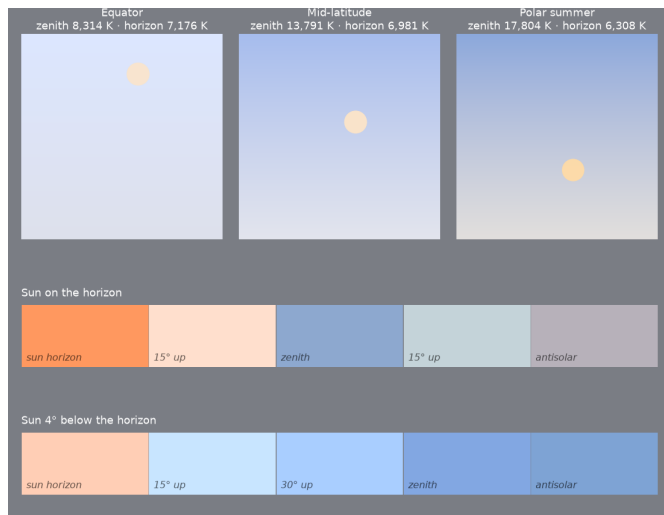


Figure 34: Late Cretaceous, 66.1 Ma. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

The Late Cretaceous: air much like today's, under a Sun half a percent fainter, over dinosaur-age forests. It is the sky of the Cretaceous before the asteroid, and of the Paleogene once the soot and sulfate of the impact winter have settled out, a couple of years after.

K-Pg impact winter, 66 Ma

months after Chicxulub: stratospheric soot ($\tau \sim 1.5$) + sulfate ($\tau \sim 0.5$)

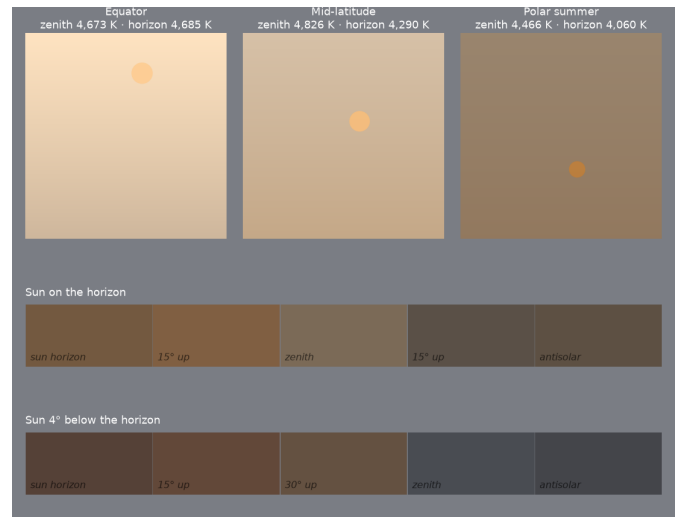


Figure 35: K-Pg impact winter, 66 Ma. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

Months after the Chicxulub impact, a global stratospheric layer of soot and sulfate turns the sky into a dim, uniform amber-beige (4,100–4,800 K) with no blue at all, about one-fifth as bright as a clear sky at the equator and 20× dimmer at high latitudes. The Sun is a pale orange disk at low latitudes and effectively gone near the poles. Sunsets do not happen as color events: the whole dome simply fades to dark brown, and the twilight sky is gray. The soot lets almost no sunlight through for over a year, and has cleared about five years after the impact (Bardeen et al. 2017); this sky shows for about two.

ζ Ophiuchi supernova, ~1.78 Ma

clean Early Pleistocene air, under a magnitude –11.6 supernova in Scorpius

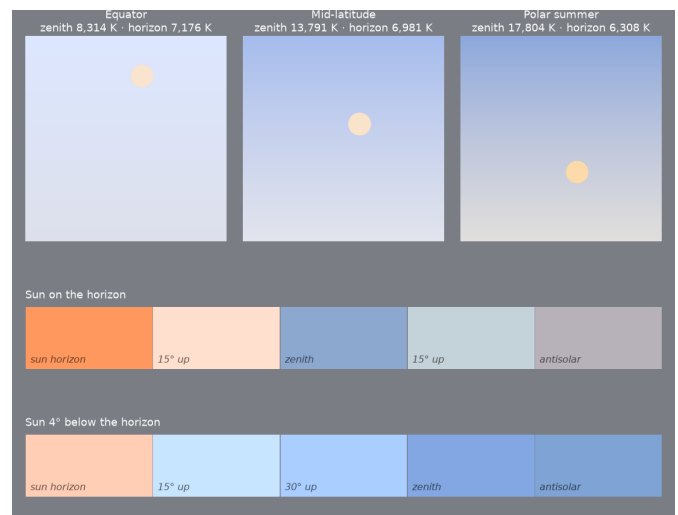


Figure 36: ζ Ophiuchi supernova, ~1.78 Ma. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

About 1.78 million years ago a star of 16 to 18 solar masses exploded in a binary in the Scorpius-Centaurus association. The explosion unbound its companion, which is now the runaway O star ζ Ophiuchi, and left a neutron star that is now the pulsar PSR B1706-16; tracing both back puts the explosion 1.78 ± 0.21 Myr ago at 107 ± 4 pc (Neuhäuser et al. 2020). Its iron-60 may be part of the ⁶⁰Fe of 1.5 to 3.2 Myr ago found in deep-sea sediments and crusts (Wallner et al. 2016) and on the Moon (Fimiani et al. 2016). A typical Type II-P supernova (Richardson et al. 2014) at that distance peaks near –11.6, about twice as bright as Geminga's, or –12.3 if the binary stripped the star and made it a Type Ib. We draw the star where a straight-line trace of ζ Oph's present motion puts it, near RA 16h10m,

Dec -21° . The stars are moved back along their measured space motions too; Antares has since traveled about 12° , and in the sky of the time the supernova sat about 12° west of it. That trace lands at 130 to 140 pc rather than 107, so the position is approximate. From mid-northern latitudes it stays low in the south. The air is clean Early Pleistocene air.

Geminga supernova, ~ 342 ka

clean Middle Pleistocene air, under a magnitude -11 supernova in Orion

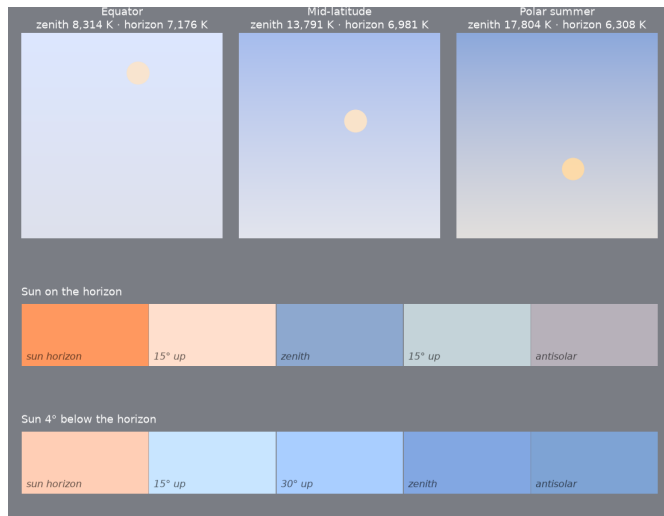


Figure 37: Geminga supernova, ~ 342 ka. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

About 342,000 years ago, going by the spin-down age of the pulsar it left behind (Salvati & Sacco 2008), a star of at most 15 solar masses exploded 90 to 240 pc away, in the direction of Orion (Pellizza et al. 2005). Type II-P supernovae peak near absolute magnitude -16.75 (Richardson et al. 2014), so from the middle of that range, 147 pc, it reached about -11 : a fifth of the full Moon's light, all from a point. The -13 often quoted needs both the near end of the distance range and an unusually bright explosion. It burned in the daytime sky as a dazzling star, cast sharp shadows at night, and held near peak for the three months of its plateau. The air is clean Middle Pleistocene air; at this distance the explosion barely touches the atmosphere (Thomas et al. 2016), so the sky's colors are today's. The star is drawn at the birthplace. The stars around it are moved back along their measured space motions, which puts it just 1.4° from Betelgeuse in the sky of the time.

Volcanic year, 1816 (Tambora)

the stratospheric sulfate veil of Tambora (April 1815) through 1816, $\tau_{550} \sim 0.4$

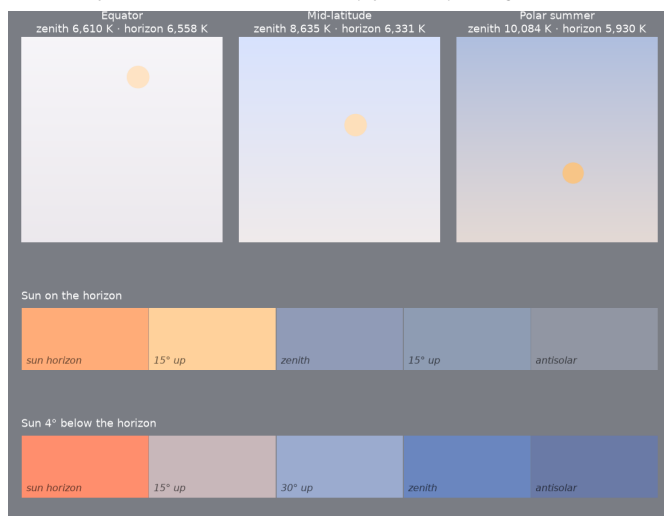


Figure 38: Volcanic year, 1816 (Tambora). Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

A Tambora-scale sulfate veil ($\tau \approx 0.4$) whitens the noon sky and lights the twilight. Noon skies are milky, a pale blue-white zenith over a white horizon, with a third of a clean sky's contrast between them. Sunsets glow salmon-orange, and the after-sunset sky $15\text{--}30^\circ$ above the horizon turns a luminous pink-lavender: the high sulfate layer is still lit when the lower atmosphere is in shadow. The veil spreads over the months after Tambora's eruption in April 1815, stays through 1816, and clears in 1817. This is the sky of Turner's 1816 paintings and of the Krakatoa twilights of 1883.

Dark nights, 1900

today's clean air over a countryside before electric light: no city glow

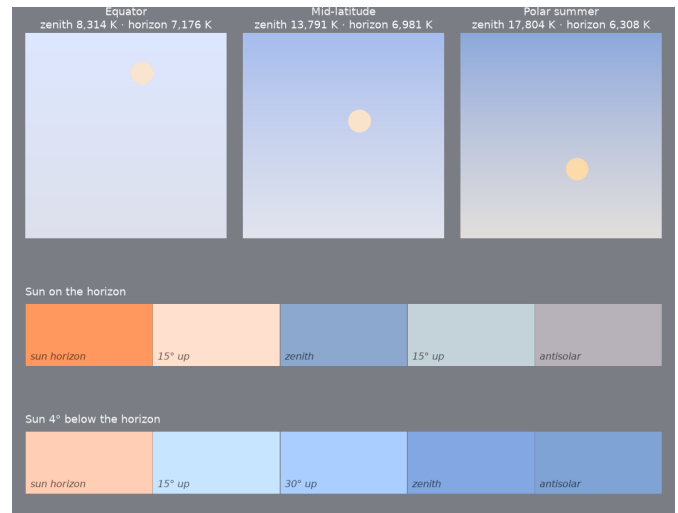


Figure 39: Dark nights, 1900. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

The sky before electric light. The air is today's clean air, but the night is dark: oil and gas lamps lit towns without lighting the sky, and the glow of cities only grew with electric light through the twentieth century, to a third of today's by 1990 and today's now. This is the sky of the whole stretch of human history before then, and of the Pleistocene back to about 170,000 years ago.

Ozone-hole spring

Antarctic spring in the ozone-hole years: column 130 DU

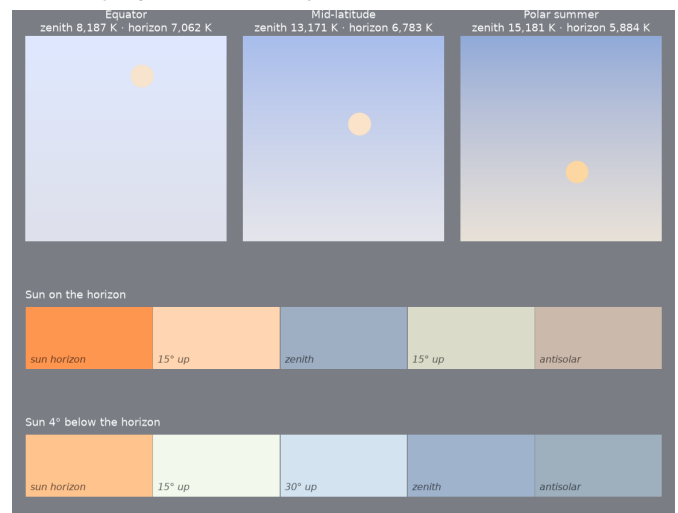


Figure 40: Ozone-hole spring. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

Antarctic spring in the ozone-hole years, with the column cut to 130 DU and the layer lowered toward 18 km. Noon stays blue. Twilight is where the hole shows: with the Sun 4° down the zenith is a pale blue ($\sim 9,900$ K) instead of the deep blue ($\sim 24,000$ K) of a 300 DU sky. It is the same direction as the thin post-oxidation column, and still well short of the gray ($\sim 6,700$ K) of a sky with no ozone at all.

Modern, clean air

aerosol optical depth 0.1; ozone 260/300/330 DU by latitude

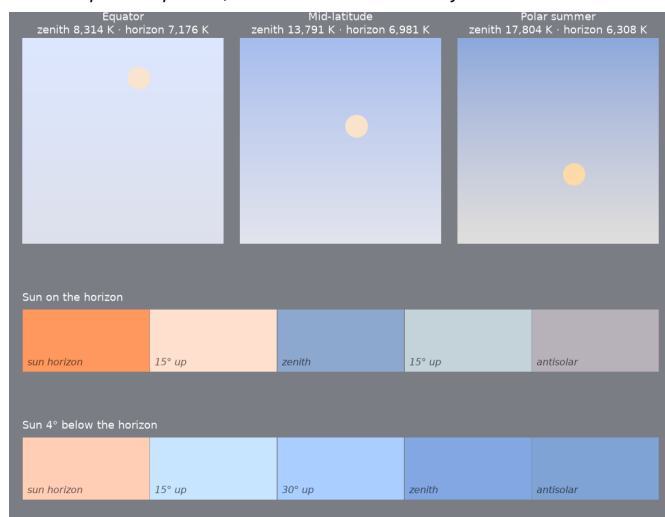


Figure 41: Modern, clean air. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

Today's clean air is the baseline the other skies are measured against. The zenith is ~8,300 K at the equator, ~13,800 K at mid-latitudes and ~17,800 K in polar summer, and the horizons, at 6,300–7,200 K, are essentially white. The setting Sun is ~1,700 K, with the solar horizon orange and the antisolar horizon a pale pink-lavender.

Modern, polluted megacity

aerosol optical depth 0.6, slightly absorbing

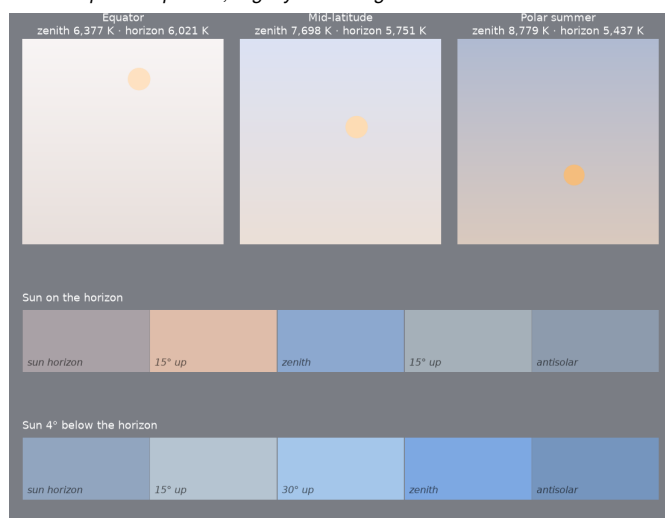


Figure 42: Modern, polluted megacity. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

Aerosol optical depth 0.6 flattens the sky to a pale gray-blue zenith (6,400–8,800 K), brighter and whiter than a clean sky, over a warm white horizon (5,400–6,000 K). The Sun disappears into gray murk well before it reaches the horizon.

Year 2100

today's clean air, with the filed megaconstellation and the Sunrise orbital datacenters

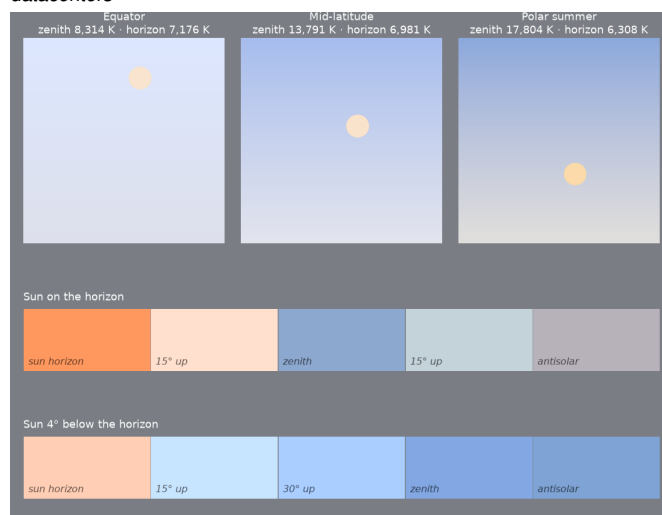


Figure 43: Year 2100. Top: noon sky dome at the equator, mid-latitude and polar summer, zenith at top, horizon at bottom, Sun's disk in its own color. Below: sky from the solar horizon to the antisolar horizon with the Sun on the horizon and 4° below it.

The air is today's. What changes is the traffic: the filed megaconstellations and, above them, the Sunrise orbital datacenters, some 1,600 brighter than fifth magnitude an hour after sunset in a band along the terminator, fading from view two and a half hours after it (Satellites, Section 9).

11 Caveats

Paleoatmospheric compositions carry order-of-magnitude uncertainty, and the haze optical properties are taken from Titan-analog tholins; the three haze cases bracket that uncertainty. Aerosol loads for every pre-Cenozoic epoch are educated guesses, and the proto-Earth's air before the last giant impact is unconstrained. The color-matching functions use an analytic fit, and colors are shown without chromatic adaptation, so the tints represent what a modern camera set to day-light balance would record rather than what an adapted observer would "see" (an adapted eye would perceive the hazy Archean sky as nearer to white and the modern sky as bluer than shown). Clouds are omitted from the radiative transfer throughout. Orders of scattering past the fourth are spread evenly in all directions, which leaves the hazy skies' zenith up to 18% bright in twilight, and the blue of the 30-bar Hadean sky is checked against no other code: CalcMySky's had not converged after 60 orders of scattering.

Between the epochs the air follows curves fitted through the epochs' own values and the few dated steps the record gives (Section 2.2); the real air wandered between them, and the events' dates and durations carry the uncertainties their sources state, tens of millions of years for the Neoproterozoic haze episodes. The grid of precomputed airs is set so that blending misses the air between by about 5% in luminance and 0.002 in chromaticity at most. Beyond the colors, the strengths of the ancient airglow, aurorae, coronae, meteor, shower and comet rates and zodiacal dust are estimates set to show the trend, as each section says; the lunar eclipses, the Moon's orbit and the stars' motions over the last two million years are computed, and the eclipse shadow assumes today's cloud tops in every epoch. Several things are drawn for the eye rather than to scale: the Sun and Moon at four times their size (so eclipses are found and timed with the enlarged disks), the sunset's dispersion up to 24 times, and the limb darkening at a fifth of its strength. Some things cannot be known and are drawn at random: where the planets stood on a given day more than 10,000 years from today, and every star more than about two million years back, where the stars are stand-ins of today's kinds passing the Sun. The Earth's axis turns by the long-term precession of [Vondrák, Capitaine & Wallace \(2011\)](#) within 200,000 years of each epoch's year, from

today's direction and tilt at that year, since its phase long ago cannot be pinned down. The Milky Way's dark clouds, star clouds and young-star fields before 30 Ma are likewise stand-ins, and its evolution is a smooth model fitted to the Galaxy's history. The scenery and the clouds are drawn, not modeled, and the invented faces of Theia, proto-Mercury, Anteros, Enyo and the molten Moon are illustrations of what such worlds would be like.

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Appendix A: computed chromaticities

Table 10: CIE 1931 chromaticity (x, y) and correlated color temperature of the noon zenith and horizon sky, and direct-Sun brightness relative to the modern equatorial Sun. The Late Cretaceous, the supernova epochs, 1900 and the Year 2100 have today's clean air and share its rows.

Epoch	Latitude	Zenith (x, y)	CCT (K)	Horizon (x, y)	CCT (K)	Sun
Proto-Earth, ~4.55 Ga	Equator	0.348, 0.358	4,931	0.359, 0.370	4,582	0.21
Proto-Earth, ~4.55 Ga	Mid-latitude	0.310, 0.333	6,595	0.374, 0.381	4,204	0.16
Proto-Earth, ~4.55 Ga	Polar summer	0.329, 0.351	5,644	0.393, 0.384	3,736	0.03
Early Hadean, ~4.50 Ga	Equator	0.405, 0.395	3,562	0.407, 0.394	3,488	0.0084
Early Hadean, ~4.50 Ga	Mid-latitude	0.405, 0.395	3,541	0.410, 0.393	3,432	0.0021
Early Hadean, ~4.50 Ga	Polar summer	0.394, 0.388	3,746	0.393, 0.387	3,752	1.4e-06
Late Hadean, ~4.0 Ga	Equator	0.307, 0.321	6,875	0.315, 0.328	6,388	0.63
Late Hadean, ~4.0 Ga	Mid-latitude	0.274, 0.284	10,896	0.322, 0.336	5,982	0.55
Late Hadean, ~4.0 Ga	Polar summer	0.274, 0.289	10,576	0.346, 0.358	4,973	0.25
Early Archean, ~3.8 Ga	Equator	0.296, 0.308	7,877	0.308, 0.323	6,816	0.77
Early Archean, ~3.8 Ga	Mid-latitude	0.266, 0.274	12,699	0.312, 0.327	6,540	0.72
Early Archean, ~3.8 Ga	Polar summer	0.262, 0.272	13,603	0.330, 0.346	5,605	0.47
Neoproterozoic, ~2.7 Ga (clear)	Equator	0.295, 0.307	7,924	0.307, 0.321	6,906	0.83
Neoproterozoic, ~2.7 Ga (clear)	Mid-latitude	0.267, 0.274	12,698	0.311, 0.326	6,637	0.78
Neoproterozoic, ~2.7 Ga (clear)	Polar summer	0.261, 0.271	13,899	0.328, 0.344	5,713	0.52
Neoproterozoic haze episode, ~2.58 Ga (thin haze)	Equator	0.310, 0.326	6,692	0.318, 0.333	6,227	0.71
Neoproterozoic haze episode, ~2.58 Ga (thin haze)	Mid-latitude	0.292, 0.307	8,212	0.324, 0.339	5,888	0.63
Neoproterozoic haze episode, ~2.58 Ga (thin haze)	Polar summer	0.294, 0.313	7,855	0.350, 0.364	4,856	0.31
Neoproterozoic haze episode, ~2.52 Ga (thick haze)	Equator	0.336, 0.355	5,363	0.344, 0.359	5,046	0.46
Neoproterozoic haze episode, ~2.52 Ga (thick haze)	Mid-latitude	0.330, 0.351	5,623	0.357, 0.371	4,644	0.35
Neoproterozoic haze episode, ~2.52 Ga (thick haze)	Polar summer	0.352, 0.374	4,819	0.396, 0.398	3,760	0.07
Neoproterozoic haze episode, ~2.52 Ga (very thick haze, upper bound)	Equator	0.380, 0.392	4,121	0.391, 0.398	3,877	0.19
Neoproterozoic haze episode, ~2.52 Ga (very thick haze, upper bound)	Mid-latitude	0.383, 0.397	4,080	0.412, 0.409	3,515	0.1
Neoproterozoic haze episode, ~2.52 Ga (very thick haze, upper bound)	Polar summer	0.416, 0.416	3,476	0.446, 0.423	2,997	0.004
Paleoproterozoic, ~2.2 Ga	Equator	0.295, 0.307	7,943	0.307, 0.321	6,887	0.87
Paleoproterozoic, ~2.2 Ga	Mid-latitude	0.268, 0.276	12,208	0.311, 0.325	6,637	0.81
Paleoproterozoic, ~2.2 Ga	Polar summer	0.261, 0.270	14,089	0.326, 0.341	5,786	0.51
Snowball Earth, ~700 Ma	Equator	0.296, 0.304	7,943	0.306, 0.318	7,023	0.99
Snowball Earth, ~700 Ma	Mid-latitude	0.259, 0.263	15,399	0.306, 0.319	6,974	0.93
Snowball Earth, ~700 Ma	Polar summer	0.255, 0.261	16,841	0.315, 0.332	6,368	0.62
Cryogenian, ~650 Ma (between the snowballs)	Equator	0.293, 0.305	8,139	0.305, 0.319	7,043	0.97
Cryogenian, ~650 Ma (between the snowballs)	Mid-latitude	0.267, 0.274	12,712	0.308, 0.322	6,815	0.9
Cryogenian, ~650 Ma (between the snowballs)	Polar summer	0.257, 0.265	15,560	0.321, 0.336	6,049	0.56
Ordovician meteor storm, ~466 Ma	Equator	0.295, 0.307	7,913	0.305, 0.318	7,033	0.95
Ordovician meteor storm, ~466 Ma	Mid-latitude	0.266, 0.273	12,937	0.308, 0.322	6,830	0.87
Ordovician meteor storm, ~466 Ma	Polar summer	0.254, 0.261	16,885	0.318, 0.333	6,181	0.5
Carboniferous, ~300 Ma	Equator	0.294, 0.308	7,956	0.308, 0.320	6,866	0.91
Carboniferous, ~300 Ma	Mid-latitude	0.268, 0.276	12,305	0.311, 0.324	6,635	0.82
Carboniferous, ~300 Ma	Polar summer	0.256, 0.265	15,737	0.323, 0.336	5,966	0.41
K-Pg impact winter, 66 Ma	Equator	0.356, 0.364	4,673	0.355, 0.362	4,685	0.12
K-Pg impact winter, 66 Ma	Mid-latitude	0.351, 0.359	4,826	0.369, 0.372	4,290	0.054
K-Pg impact winter, 66 Ma	Polar summer	0.363, 0.367	4,466	0.378, 0.374	4,060	0.00038
Volcanic year, 1816 (Tambora)	Equator	0.311, 0.325	6,610	0.312, 0.325	6,558	0.67
Volcanic year, 1816 (Tambora)	Mid-latitude	0.289, 0.300	8,635	0.316, 0.329	6,331	0.53
Volcanic year, 1816 (Tambora)	Polar summer	0.278, 0.289	10,084	0.323, 0.334	5,930	0.13
Ozone-hole spring	Equator	0.292, 0.305	8,187	0.305, 0.319	7,062	1
Ozone-hole spring	Mid-latitude	0.265, 0.272	13,171	0.309, 0.323	6,783	0.94
Ozone-hole spring	Polar summer	0.258, 0.266	15,181	0.324, 0.339	5,884	0.57
Modern, clean air	Equator	0.291, 0.304	8,314	0.303, 0.317	7,176	1
Modern, clean air	Mid-latitude	0.263, 0.270	13,791	0.306, 0.320	6,981	0.92
Modern, clean air	Polar summer	0.252, 0.259	17,804	0.316, 0.332	6,308	0.53
Modern, polluted megacity	Equator	0.315, 0.329	6,377	0.322, 0.333	6,021	0.6
Modern, polluted megacity	Mid-latitude	0.297, 0.310	7,698	0.327, 0.338	5,751	0.45
Modern, polluted megacity	Polar summer	0.287, 0.300	8,779	0.334, 0.342	5,437	0.08

Appendix B: our sky model and CalcMySky

CalcMySky (Kabatsayev 2025) is the atmosphere code behind ShowMySky, the optional sky model Stellarium has shipped since version 1.0 (Zotti & Wolf 2023). It follows the precomputed atmospheric scattering of Bruneton & Neyret (2008): a command-line tool, *calcmysky*, precomputes a model on the GPU from a plain-text description of the atmosphere, and a runtime library, *libShowMySky*, renders it in real time for any geometry. It is meant for unusual atmospheres too, Mars among its samples, which makes it the natural independent check on ours. There is no refereed paper on CalcMySky itself; Zotti & Wolf describe it in Stellarium. Table 11 sets the two approaches side by side.

Table 11: Our sky model (*skymodel.py*) and CalcMySky v0.4.0.

	Ours	CalcMySky
Geometry	Spherical shell, straight rays, observer on the ground	Spherical shell, straight rays, observer at any altitude up to the top of the atmosphere
Single scattering	Integrated numerically along each view ray, with the columns toward the Sun at every point and the Earth's shadow	Exact, in a precomputed four-dimensional texture
Multiple scattering	A table over altitude and the Sun's local elevation (Hillaire 2020), gathered from each node by rays in 576 directions; all orders solved exactly as a linear system per wavelength, with the ground lit by the scattered light too; orders 2–4 keep their directions and later orders are spread evenly. The altitudes adapt so that no two neighbors are more than 0.3 apart in optical depth	Every order computed explicitly in spherical geometry, with its directions, up to a set number of orders (the sample Earth uses 4, Mars 8)
Spectrum	41 wavelengths, 380–780 nm	Set by the user; its samples use 16 wavelengths, 360–830 nm
Constituents	Rayleigh gas mix, ozone (Serduchenko et al. 2014), tropospheric aerosol, sulfate, tholin haze, soot and dust, each with its own profile, spectral optical depth and single-scattering albedo	Any number of scatterers, each with a density profile and a phase function written in GLSL, a cross-section with an Ångström exponent and a spectral single-scattering albedo; absorbers with spectral cross-sections
Phase functions	Rayleigh and Henyey–Greenstein	Anything written in GLSL, chromatic or not
Surface	Lambertian, albedo 0.08, 0.18 or 0.70 by latitude, and 0.75 everywhere over the Snowball's ice	Lambertian, one albedo spectrum over the whole globe
Inhomogeneity	Cloud-shadow shafts, computed apart from the sky's radiative transfer (Section 3.7)	None: the atmosphere is spherically symmetric
Refraction	None in the sky's radiance; exact in the lunar eclipse's ray trace and the setting Sun's image	None
Solar eclipses	Drawn over the computed sky (Section 4.5)	In the radiative transfer, up to the second order of scattering
Output	Precomputed per air: 34 solar zenith angles $\times$ 9 view zenith angles $\times$ 10 azimuths $\times$ 3 latitudes, interpolated on the site	Any geometry in real time, from the textures
Validation	Against measured modern colors, and against CalcMySky (below)	The method family is evaluated against libRadtran and measured skies by Bruneton (2017)

The cross-check

Each epoch's atmosphere, as our model builds it, is written out as a CalcMySky description (*calcmysky_check.py*): every component's own vertical profile, its optical depth as a power law in wavelength (fitted to within 10^{-13}), its spectral single-scattering albedo and its phase function, ozone as an absorber with the same cross-sections, the epoch's Sun as the same Planck spectrum, a ground albedo of 0.18, and 44 wavelengths from 380 to 810 nm. CalcMySky's radiance textures are read back at the ground on the grid the site uses, with single and multiple scattering kept apart, and compared with ours at mid-latitude. CalcMySky ran 10 orders of scattering for the modern and hazy Archean skies, 20 for the very thick haze and the impact winter, and up to 60 for the 30-bar Hadean.

Single scattering checks the setup: ours matches CalcMySky's within 0.7% in every epoch until the Sun is 4° below the horizon. Further down, where nearly all the light has been scattered more than once, the two differ by 10% or more, which hardly changes the total. The inputs are therefore the same, and what differs is the multiple scattering (Table 12, Figure 44).

Table 12: Zenith luminance, ours $\div$ CalcMySky, at mid-latitude. τ_{450} is the total optical depth at 450 nm.

Solar zenith angle	Modern (τ_{450} 0.34)	Hazy Archean, 2.52 Ga (0.91)	Very thick haze (1.8)	K–Pg impact winter (1.7)
0°	1.01	1.00	1.01	1.00
30°	1.01	1.02	1.03	1.02
60°	1.01	1.04	1.07	1.04
84°	1.00	1.06	1.10	1.04
90°	1.00	1.07	1.10	1.04
93°	0.99	1.05	1.05	1.02
96°	1.00	1.15	1.14	1.04
100°	1.01	1.18	1.15	1.06
104°	1.01	1.16	1.09	1.03
108°	1.02	1.10	0.99	1.02

The modern sky agrees within 3% at the zenith from noon until the Sun is 20° down, and the zenith's chromaticity within 0.002, through the ozone blue of deep twilight, which takes the zenith to about (0.20, 0.20). At the horizon (view zenith angle 84°) it agrees within 0.99–1.08 on the side toward the Sun until the Sun is 10° down, and within 0.93–1.01 on the side away from it throughout. Across the whole sky it agrees within 0.90–1.10 in brightness and 0.006 in chromaticity until the Sun is 6° down. Below that, a few directions low on the Sun's side, toward the last sunlit air, differ by up to a factor of 3.

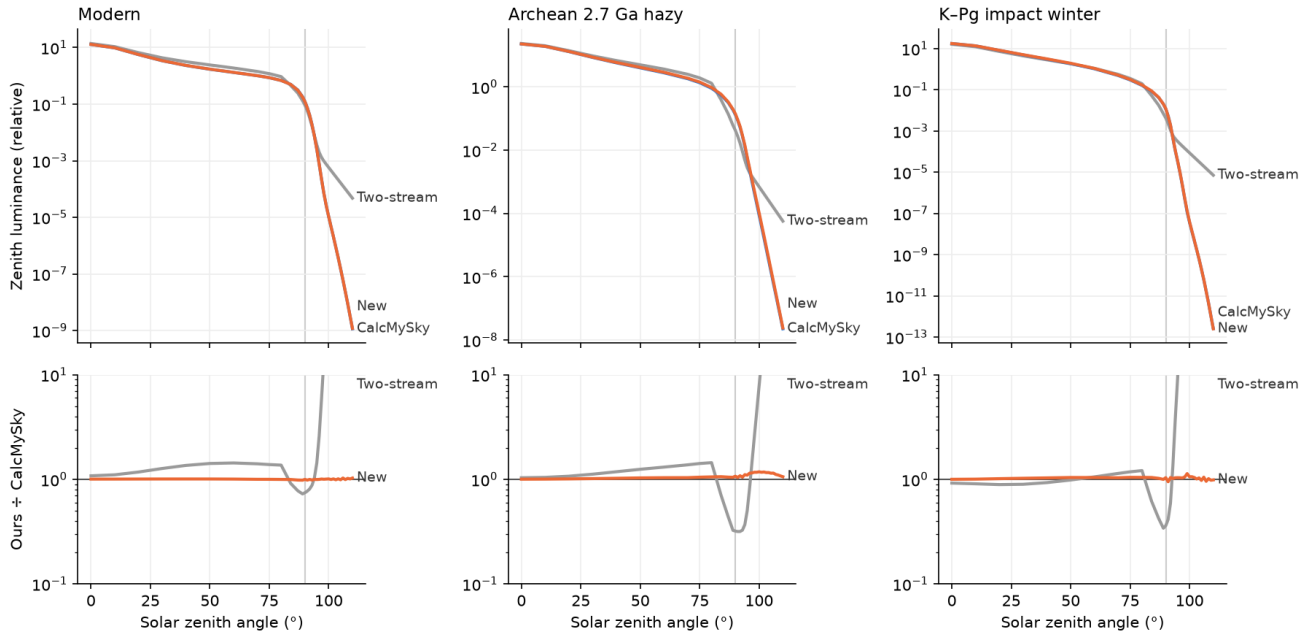


Figure 44: Zenith luminance against the Sun's zenith angle (top) and its ratio to CalcMySky (bottom), for our model ("New"), CalcMySky, and the delta-Eddington two-stream term (Toon et al. 1989) that carried our multiple scattering before, the same in every direction and faded by hand past a solar zenith angle of 80°.

The hazy skies run bright at the zenith: by 0–10% by day, and by up to 18% in twilight. Their zenith chromaticity agrees within 0.006 until the Sun is 20° down, through the Archean's deep-twilight orange, and the whole sky's within 0.021. At the horizon, the side toward the Sun agrees within 0.92–1.04 until sunset. It then falls to 0.78–0.84 of CalcMySky by the time the Sun is 10° down, and to 0.5–0.7 at 20° in the two thickest skies. The side away from the Sun stays within 0.82–1.07. The excess comes from spreading the fifth and later orders evenly: with the hazes made isotropic in both models, ours matches CalcMySky within 5% at the zenith until the Sun is 20° down. Raising CalcMySky's own resolution moves its result by 0–5% at the zenith.

The 30-bar Hadean ($\tau \approx 12$ at 450 nm) is where CalcMySky stops being a reference. A thick, nearly lossless layer needs on the order of τ^2 orders of scattering. From 30 to 60 orders, CalcMySky's zenith multiple scattering still grew $2.8\times$ at 380 nm, $1.6\times$ at 450 nm and 4% at 600 nm, while from 650 nm up its whole sky changed by 1% or less. Sixty orders took 2.6 hours on an RTX 3080. In the converged 650–750 nm, our zenith is 0.95–1.09 of CalcMySky from noon until the Sun is 10° down. Our horizon is brighter than CalcMySky's, by up to 7% at 750 nm, 12% at 700 nm and 22% at 650 nm, and its brightest direction is $1.46\times$ CalcMySky's. Our solve sums every order, so its blue is converged by construction. It is checked instead against the delta-Eddington two-stream flux at the ground, which is good in so thick a layer, and agrees with it within 3–5% from 450 nm up.

Where each goes further

CalcMySky follows every order of scattering with its directions, where ours spreads the fifth and later orders evenly. It renders any geometry in real time, from any altitude, with solar eclipses in the radiative transfer and phase functions of any shape, and every atmosphere goes through exactly the same calculation, so atmospheres differ only in their inputs. Its cost grows with the number of orders, though, which puts the blue of an atmosphere as thick as the Hadean's beyond it. Ours sums every order in one linear solve, so its cost hardly depends on how thick the air is: a table takes about 15 s on the same GPU, or 59 s for the Hadean. Beyond the radiative transfer, ours carries what a spherically symmetric model cannot (albedo that changes with latitude, the shadows of clouds, refraction where it shows, in the eclipsed Moon and the setting Sun, and the views from space), and it adds the researched deep-time atmospheres themselves and the color science on top: spectra, chromaticities and color temperatures, checked against measured modern skies. CalcMySky supplies the machinery for any atmosphere, but each one still has to be written and justified.