

Borealis Horizon: a real-time relativistic voyage to the Pillars of Creation — model, implementation and limitations

Borealis Dynamics

Public experiment at <https://ngc6611.pages.dev> · site version 1.1.0 · liftoff on 19 October 2026, 12:00 (UTC-3) · document dated 19 Oct 2026

ABSTRACT

Borealis Horizon is a public, browser-based simulation of an interstellar voyage at a constant proper acceleration of 1 g from Earth to a point 7 light-years short of the Pillars of Creation (M16), covering 6,985 light-years in Earth's frame. The simulation runs in real time from a launch instant fixed at publication: every ship second, the observer sees the kinematic state predicted by the model — obtained by numerical integration during the ascent and by closed-form expressions in the relativistic acceleration and braking phases — and the sky a fixed-exposure camera would record. This paper documents the physical model (closed-form hyperbolic motion with an initial Newtonian phase integrated by Runge–Kutta; time dilation; signal delay and the acceleration horizon; aberration and Doppler shifts of color and brightness; interstellar extinction; the cosmic microwave background transformed direction by direction; a three-dimensional reconstruction of the Eagle Nebula from public photographs; an ideal photon rocket), the implementation choices (numerically stable formulations for γ up to $\sim 10^4$, precomputed tables, flux-conserving integration, verification by regression tests) and the known limitations. With $\gamma = 3,606$ at turnaround, 17.21 ship years and 6,987 Earth years, the voyage is presented as a visualization experiment: faithful where physics is computable and openly simplified where engineering or data do not exist.

Keywords: special relativity; hyperbolic motion; aberration; Doppler effect; cosmic microwave background; Eagle Nebula; scientific visualization; WebGL.

1. Introduction and experimental design

Voyages at constant proper acceleration are the classic example of how special relativity turns galactic distances into human durations: rapidity grows linearly with proper time, and the distance covered grows exponentially with it [1, 2]. What one rarely sees is the *appearance* of such a voyage — how the sky compresses forward, how the colors change, how the cosmic microwave background (CMB) becomes a visible spot, how the image of Earth freezes behind the ship — presented without shortcuts, with the correct numbers, over the actual duration of the voyage.

Borealis Horizon is that experiment. The ship departs from a fictional coastal base, climbs with a thrust of 1.1 g, switches to a constant proper acceleration of 1 g, reverses thrust halfway along the route and stops, at rest relative to Earth, 7 light-years before the plane of the Pillars of Creation, after 6,985 light-years. The simulation runs in an ordinary web browser (HTML, JavaScript and WebGL2, with no external libraries), and the departure instant, $T_0 = 19$ October 2026, 12:00:00 UTC-3, was stamped at publication: all visitors see the same ship, at the same point, in real time. There is no time acceleration, pause or rewind; the voyage lasts 17.21 ship years of actual time on the site.

The design follows three principles. (i) *Fidelity where there is computation*: kinematics, clocks, light and the cosmic background are computed from physical laws, without staged effects. (ii) *Fixed exposure*: the gain and the tone-compression function of the window are fixed in advance, with no automatic exposure

adjustment to the scene. (iii) *Declared simplification*: what engineering does not know how to do (the engine, the shield) and what the data do not contain (the third dimension of the nebula) is stated explicitly and listed for the public on the site's "Poetic licence" page. This paper is the technical counterpart of that list: it describes the model, the formulas, the implementation and the known problems.

Section 2 presents the motion model; Section 3, time and signals; Section 4, light (aberration, Doppler, extinction, catalogs, exposure, Earth); Section 5, the cosmic background; Section 6, the reconstruction of the Eagle Nebula; Section 7, propulsion, energy and the flux on the shield; Section 8, the scenic encounters; Section 9, the instruments, the ship's log and the ship radio; Section 10, implementation and numerical robustness; Section 11, limitations and known problems. The appendices collect constants, parameters and milestones.

2. Motion model

2.1 Ascent phase ($\tau < 24$ h)

The trajectory is a pure function of ship time τ (seconds since departure), defined in two phases. In the first, which lasts exactly one ship day, the ship climbs radially from Earth's surface under terrestrial gravity and a thrust per unit mass

$$a(r) = \max\left(1.1 \frac{GM}{r^2}, g_0\right), \quad (1)$$

with $GM = g_0 R_\oplus^2$ ($g_0 = 9.80665$ m/s², $R_\oplus = 6,371$ km), so that the thrust is 1.1 g on the pad and switches to g_0 when $1.1 GM/r^2$ falls below g_0 , at 311 km altitude ($r = R_\oplus \sqrt{1.1}$). The resulting acceleration is $a(r) - GM/r^2$: 0.1 g net at the start, rising to practically 1 g as Earth's gravity fades. There is no atmosphere, drag, Earth rotation, Sun or Moon in this phase (Section 11). The system

$$\frac{dr}{d\tau} = v, \quad \frac{dv}{d\tau} = a(r) - \frac{GM}{r^2} \quad (2)$$

is integrated by fourth-order Runge–Kutta with a prescribed variable step $h = 0.02 + 5 \times 10^{-4} \tau$ (from 20 ms on the ground to 43 s at the end of the day), storing tables of τ , r , v and the acceleration. Since $v \ll c$ throughout the day (827 km/s at the end), the phase is treated as Newtonian; the relativistic correction enters through two integrals accumulated along with the state: the *burn* b (rapidity accumulated by thrust, Section 7),

$$b(\tau) = \frac{1}{c} \int_0^\tau a(r(\tau')) d\tau', \quad (3)$$

integrated by Simpson's rule in each step, and Earth time $t_\oplus$, with time dilation to first order in v^2/c^2 ,

$$dt_\oplus = \left(1 + \frac{v^2}{2c^2}\right) d\tau, \quad (4)$$

evaluated with the mean of v^2 at the step endpoints. At the end of the day the ship is 34.9 million kilometers from Earth's center, at 827 km/s, with $t_\oplus - \tau = 0.107$ s. Between table nodes, the state is interpolated by cubic Hermite polynomials using the known derivatives (v for r , a for v), which preserves the continuity of r , v and the reported acceleration.

2.2 Relativistic phase: closed-form hyperbolic motion

From $\tau_1 = 86,400$ s on, the proper acceleration is constant, $a = g_0$, and the trajectory is Rindler's hyperbolic motion [1, 3]. With the rapidity η defined by $\beta = \tanh \eta$ and $\gamma = \cosh \eta$, constant proper acceleration gives

$$\eta(\tau) = \eta_1 + \frac{a}{c}(\tau - \tau_1), \quad (5)$$

with $\eta_1 = \operatorname{artanh}(v_1/c) = 2.76 \times 10^{-3}$ the rapidity at the end of the ascent. The radial position and Earth time follow, for $\tau_1 \leq \tau < \tau_F$,

$$r = r_1 + \frac{c^2}{a} \cdot 2 \sinh \frac{\eta + \eta_1}{2} \sinh \frac{\eta - \eta_1}{2}, \quad t_{\oplus} = t_1 + \frac{c}{a} \cdot 2 \cosh \frac{\eta + \eta_1}{2} \sinh \frac{\eta - \eta_1}{2}, \quad (6)$$

which are the identities $\cosh \eta - \cosh \eta_1 = 2 \sinh((\eta + \eta_1)/2) \sinh((\eta - \eta_1)/2)$ and $\sinh \eta - \sinh \eta_1 = 2 \cosh((\eta + \eta_1)/2) \sinh((\eta - \eta_1)/2)$ written without subtracting two nearly equal numbers (Section 10). Turnaround occurs at the rapidity η_F such that symmetric braking, from η_F to zero, covers exactly the remaining distance to the destination $D = 6,985$ ly:

$$\cosh \eta_F = \frac{1}{2} \left[\frac{a(D - r_1)}{c^2} + \cosh \eta_1 + 1 \right], \quad (7)$$

obtained by setting $r(\eta_F) + (c^2/a)(\cosh \eta_F - 1) = D$. During braking ($\tau_F \leq \tau < \tau_{\text{fim}}$) the rapidity decreases linearly, $\eta = (\tau_{\text{fim}} - \tau) a/c$, and the remaining distance is

$$D - r = \frac{c^2}{a} \cdot 2 \sinh^2 \frac{\eta}{2}, \quad t_{\text{fim}} - t_{\oplus} = \frac{c}{a} \sinh \eta. \quad (8)$$

Table 1 summarizes the values. The scale $c/a = 0.9687$ year is the natural constant of the voyage: every 0.9687 ship year adds one unit of rapidity; each additional "9" in the fraction of the speed of light costs the same stretch of tape, as shown by the rapidity tape on the velocity panel.

Table 1. Characteristic values of the trajectory ($a = g_0$, $D = 6,985$ light-years).

Quantity	Value	Remark
End of ascent, τ_1	86,400 s	$r_1 = 3.49 \times 10^7$ km, $v_1 = 827$ km/s, $\eta_1 = 2.76 \times 10^{-3}$
Rapidity at turnaround, η_F	8.8836	$\gamma_F = 3,606.3$; $1 - \beta_F = 3.84 \times 10^{-8}$ (41.5 km/h short of c)
Turnaround, τ_F	8.6057 years	$t_{\oplus} = 3,493.47$ years; $r_F = 3,492.5$ ly
Arrival, τ_{fim}	17.2114 years	6,286.5 ship days; $t_{\oplus} = 6,986.94$ years
Maximum proper velocity, $\gamma\beta c$	7.23 AU/s	distance on the Galaxy map per ship second
Contracted path at turnaround, D/γ_F	1.94 ly	the entire route, measured on board
Total burn, b_{fim}	17.7672	mass ratio $e^b = 5.20 \times 10^7$ (Section 7)

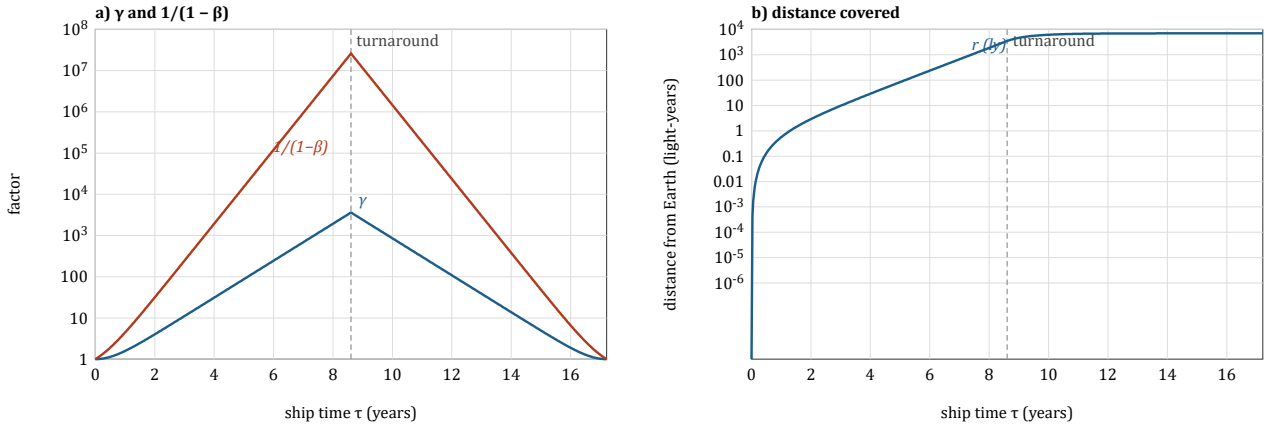


Figure 1. Kinematics of the trip as a function of ship time, from equations (5)–(8): (a) the Lorentz factor $\gamma = \cosh \eta$ and $1/(1 - \beta) = (e^{2\eta} + 1)/2$ grow exponentially up to the turnaround ($\gamma = 3,606$; $1 - \beta = 3.8 \times 10^{-8}$) and decrease symmetrically while braking; (b) the distance from Earth in light-years, on a logarithmic scale — the ship crosses 1 light-year at 1.29 years of ship time and half the route (3,492.5 ly) at the turnaround.

2.3 Instantaneous state and milestones

For any τ the state function returns the phase, τ , $t_{\oplus}$, r , v , η , β , γ , $\varepsilon = 1 - \beta$, the reported acceleration and the burn. Milestones defined by a distance or by a physical quantity (escape from Earth's gravity, planetary orbits, 1 light-day, heliopause, Oort cloud, Local Bubble, CMB temperature thresholds, distances of reference stars) are solved by bisection on the state function, with at most 200 iterations and stopping when the midpoint coincides with an endpoint in double precision; fixed-duration and calendar milestones are constructed directly. A milestone such as "Distance of Proxima Centauri" means reaching, from Earth, that star's distance (4.25 ly) — not passing by it. The same state feeds all panels, the ship's log, the radio and the sky: there is no second source of truth.

3. Time and signals

3.1 Clocks

The ship clock is the visitor's real clock, aligned to the server's by the Date header of a HEAD request — an alignment estimate, not a guarantee: the header has a resolution of 1 s, the network may be asymmetric and, if the request fails, the local clock is used — and $\tau = t_{\text{now}} - T_0$. The "Earth ahead" panel shows $t_{\oplus} - \tau$ with a dynamic unit. At first the difference grows as $a^2 \tau^3 / (6c^2)$, by (4): 1.8 attoseconds in the first second, 1 picosecond only at 82 s — below the resolution of the double-precision integration in the first seconds, which is the reason for the panel's picosecond floor; at arrival Earth is 6,970 years ahead. The proper velocity, $\gamma\beta c$, is shown on the velocity panel: at turnaround the ship advances 7.23 AU of the Galaxy map per ship second. The navigation panel shows the remaining distance measured on board (the distance in Earth's frame divided by γ) and how much the contraction has already shortened the way; divided by γ_F , the entire route would be 1.94 light-years.

3.2 Clock reference frames

Three times appear on the instruments, and they should not be confused. τ is the ship's proper time — the ship clock. $t_{\oplus}$ is the coordinate time of the inertial frame in which Earth is at rest, the model's "Earth time"; $t_{\oplus} - \tau$ is the lead accumulated by that clock over the ship clock, but it is not something the rear camera can show: the incoming image was emitted at $t_{\oplus} - x/c$, much earlier (Section 3.3), and simultaneity in the ship's instantaneously comoving frame is yet another construction, not used in the panels. Likewise, $\gamma\beta c$ is distance in Earth's frame per proper second of the ship; locally, nothing exceeds c . General relativity is

outside the model: Earth's gravity enters as a Newtonian force during the ascent, but there is no gravitational correction of the clocks. The scale of what is omitted is not negligible compared with the precision displayed: the potential at Earth's surface ($\Delta\Phi/c^2 \approx 7 \times 10^{-10}$) accumulates ~ 150 s over 6,987 years, and that of the Sun at 1 AU ($\approx 10^{-8}$), ~ 36 min — "Earth time" to the second depends on the chosen reference frame and potential [22].

3.3 Signal delay and acceleration horizon

The link with Earth is treated with Earth fixed at the departure point and light traveling in straight lines (Earth's 8-light-minute orbit is neglected next to 6,985 light-years). With $x = r - R_\oplus$, the image of Earth that reaches the ship in state $(t_\oplus, x)$ was emitted at $t_\oplus - x/c$, and a signal emitted by the ship reaches Earth at $t_\oplus + x/c$. For an observer accelerating at g from rest there is a horizon: signals emitted at the origin after $t_\oplus = c/a = 0.9687$ year never reach the ship while it accelerates [3]. The simulation does not impose this fact; it emerges from (6): at turnaround, the light arriving from Earth was emitted only 0.9686 year after departure and is 3,492.5 years old; at arrival, it was emitted 1.937 years after departure.

Besides being old, the image of Earth runs in slow motion and reddened by the rear Doppler factor

$$D_{\text{ré}} = \sqrt{\frac{1-\beta}{1+\beta}} = e^{-\eta}, \quad (9)$$

equal to 1/7,213 at turnaround: one ship second shows 1/7,213 of an Earth second, and the light arrives 7,213 times redder. The Sun seen astern is a blackbody of 5,772 K seen at $T' = 5,772 e^{-\eta} = 0.80$ K at turnaround — colder than the cosmic background — and an FM station at 100 MHz would arrive at 13.9 kHz. The rear camera shows the emission date, the light age and the slow-motion factor, computed from these expressions.

3.4 Calendar

The duration counters use years of 365.25 days (31,557,600 s) and months of one twelfth of a year; dates are obtained by adding τ or $t_\oplus$ to the departure instant — fixed in UTC (19 October 2026, 15:00:00 UTC, presented as 12:00 UTC-3) — and formatted in the visitor's local time zone; the ship's log calendar uses Brasília time. No real communication exists: the panel computes the delay a signal would have; the ship radio is fiction written for the trip (Section 11).

4. Light

4.1 Aberration

Each source at rest in the Galaxy frame is seen by the ship in an aberrated direction. With θ the angle between the source and the direction of motion in the Galaxy frame and θ' the observed angle, the exact relation is

$$\tan \frac{\theta'}{2} = e^{-\eta} \tan \frac{\theta}{2}, \quad (10)$$

the "half-angle formula" [4]. It is preferred to the usual form $\cos \theta' = (\cos \theta + \beta)/(1 + \beta \cos \theta)$ because it remains stable as $\beta \rightarrow 1$: $\tan(\theta/2)$ is computed as $\sin \theta/(1 + \cos \theta)$ for the forward hemisphere and $(1 - \cos \theta)/\sin \theta$ for the rear one, without cancellation, and the factor $e^{-\eta}$ compresses the forward hemisphere ($\theta < 90^\circ$) into a cone of angular radius $2 \cdot \text{atan}(e^{-\eta}) \approx 2e^{-\eta}$ around the bow; the exactly rearward direction remains behind. At turnaround the forward hemisphere fits within a circle of 0.016° radius — what the

aberration panel calls "half the sky in a circle of θ' ". The same formula, inverted, is used for the nebula, the diffuse Milky Way and Earth: the ray is integrated in the rest frame, and the radiance is transformed at the end.

4.2 Doppler: color and brightness

The Doppler factor of a source seen in the direction θ' is $D = 1/[\gamma(1 - \beta \cos \theta')]$. For $\gamma \sim 10^3$ the expression $1 - \beta \cos \theta'$ loses digits near the bow — measurably in double precision and severely in the shader's float32, whose machine epsilon (6×10^{-8}) exceeds $1 - \beta$ at turnaround; the implementation uses the equivalent form

$$D = \frac{1}{\gamma[\varepsilon + 2\beta \sin^2(\theta' / 2)]}, \quad \varepsilon = 1 - \beta = \frac{2}{e^{2\eta} + 1}, \quad (11)$$

in which ε is obtained directly from the rapidity, without subtracting β from 1 (Section 10). A star treated as a blackbody of temperature T appears as a blackbody of temperature $T' = D \cdot T$; an emission line of wavelength λ appears at $\lambda' = \lambda/D$; the flux of a point source scales as D^2 and the radiance of an extended source as D^4 [5]. For stars of the HYG catalog, which have their own velocities, the Doppler shift of the star relative to the Galaxy frame is included in the same logarithm. It is from these three rules, applied to each star, that the starbow emerges: ahead, cool stars (3,000–4,000 K) shifted by $D \sim 2$ –3 turn white and blue, hot stars vanish into the ultraviolet, and the sky behind dims and reddens.

4.3 Spectra, colors and catalogs

Stellar spectra are blackbodies. The temperature-to-color conversion uses the CIE 1931 color matching functions in the analytic fit of Wyman, Sloan and Shirley [6], numerically integrated with Planck's law between 360 and 830 nm, and the XYZ→linear sRGB matrix; the result is the fraction of the bolometric power that falls in each channel, tabulated at 1,024 temperatures from $\log_{10} T = 0.5$ to 9.5 and sampled in the shader with interpolation (no color steps). The radiance of a star of visual luminosity L_V at distance d is L_V/d^2 in units of $L_\odot/(4\pi \text{ ly}^2)$, with the HYG temperature estimated from the B–V color (Ballesteros 2012 [7]; B–V = 0.65 when missing) and that of the Gaia supplement from the spectral class.

The catalog has 299,858 stars: the 109,400 of HYG v4.1 [8], with positions, velocities and epoch J2000, and 190,458 selected from the Gaia EDR3/Hipparcos/Tycho distribution prepared for Celestia [9] ($V < 9$ along the route, $V < 9$ at Earth or $V < 13$ within 15° of the destination), deduplicated by HIP/HD. The positions are three-dimensional, so that parallax along the route is geometric, not staged. For HYG, the displayed position is the retarded one: the emission instant t_e is solved by fixed-point iteration such that light emitted at $p + v \cdot (t_e - \text{epoch})$ reaches the observer in the current year, anchoring the solution to the position observed at the catalog epoch. There is no scintillation, zodiacal light or gravitational lensing.

4.4 Interstellar extinction

The dust is an explicit axisymmetric disk, with optical depth integrated between observer and source,

$$\tau = K \int_0^d e^{-|z|/H} ds, \quad K = 5.1 \times 10^{-4} \text{ ly}^{-1}, \quad H = 330 \text{ ly}, \quad (12)$$

with the Sun 65 ly from the plane; K is equivalent to 0.55 magnitude per thousand light-years in the plane. The integral has a closed form along a straight segment (Appendix A). Extinction is applied *differentially*: the catalog magnitude already includes the extinction up to Earth, so the Earth–star optical depth is subtracted and the ship–star optical depth is added, so that a star keeps its measured brightness while the ship is near Earth. The spectral dependence uses factors $\exp(-\{-0.18, 0, 0.30\} \cdot \tau)$ in the R, G and B

channels. The diffuse glow of the Milky Way is a disk model with density $0.055 \cdot e^{-R/8500} \cdot e^{-|z|/700}$ (light-years), a 5,000 K spectrum and the Galactic center at 26,670 ly, integrated in 28 logarithmic steps out to 72,000 ly, with the same dust; the Magellanic Clouds, M31 and M33 are particle clouds with the approximate shape. Queries to the Bayestar three-dimensional map did not respond during preparation, so no real dust cloud is represented (Section 11).

4.5 Fixed exposure, PSF and conversion to the screen

The renderer is HDR: the flux of each star is accumulated in a half-precision *buffer*, in physical units, with a fixed gain E chosen once ($E_{\text{dark}} = 5,400$ in the reference calibration of 1,200 px/rad, scaled with $(\text{px/rad})^2$ so that the brightness is independent of resolution). An unresolved star is drawn as a compact Gaussian, $\sigma = \max(0.55 \text{ px}, 1.2 \times 10^{-4} \text{ rad} \cdot \text{px/rad})$, with no artificial glowing disk; a physical disk appears only when the aberrated angular radius exceeds 1.2 px. The conversion to the screen is a fixed SDR compression, not a simulated eye nor an automatic exposure:

$$m = \text{mix}\left(\frac{c(1 - e^{-L})}{L}, 1 - e^{-c}, s\left(\frac{L}{12}\right)\right), \quad m' = 1.03 \frac{m^2}{m + 0.03}, \quad \text{output} = m'^{1/2.2}, \quad (13)$$

where c is the linear color, L its luminance and $s(L)$ a smooth transition between 1.5 and 12 that shifts from preserving hue to saturating per channel. With this calibration, at rest every star down to magnitude 7 appears and the rendering limit lies in the magnitude 8 range — the criterion is one pixel above a fixed brightness threshold on the screen, verified by a CPU replica of the shader over the catalog (Section 10). Taking magnitude 8.0 as an approximate reference and 6.5 as the reference for naked-eye observation under a dark sky, the difference corresponds to sources with about four times less flux ($10^{0.4 \cdot 1.5} \approx 4$). This comparison characterizes the chosen exposure; it does not constitute a calibration of human vision. The counts — about 56,000 stars rendered over the whole sky, versus $\sim 9,000$ visible to the naked eye — refer to the whole sky and do not measure sensitivity. The rear camera uses the same gain.

4.6 Earth, atmosphere and launch base

Earth is drawn as a textured sphere with the Blue Marble: Next Generation composite of January 2004 ($2,048 \times 1,024$) [20] and the Blue Marble Clouds cloud cover, the latter with continuous procedural detail in two spherical layers (1.5–3.8 km and 8.5–9.3 km altitude) so that the camera's approach does not reveal pixels. The surface receives sunlight with the terminator of the departure instant and a single-scattering atmospheric halo; the daytime sky seen from the base darkens between 50 and 100 km altitude, as a visual choice, keeping the limb lit. The base is scenery: latitude equal to the declination of M16 (-13.88° , imposed by the route axis), visual longitude fixed at -39.02° , camera at 35 m, a 112 m tower, procedural coastline and river; the details of the base disappear at 12 km and the whole ensemble at 90 km. The displayed orientation of Earth does not rotate (Section 11). When Earth shrinks to less than 1.2 px of apparent radius it becomes a point, a blackbody of 5,772 K with a luminosity of $1.36 \times 10^{-10} L_\odot$ and a bluish tint, and any star lying behind the disk is occulted by the scene Earth.

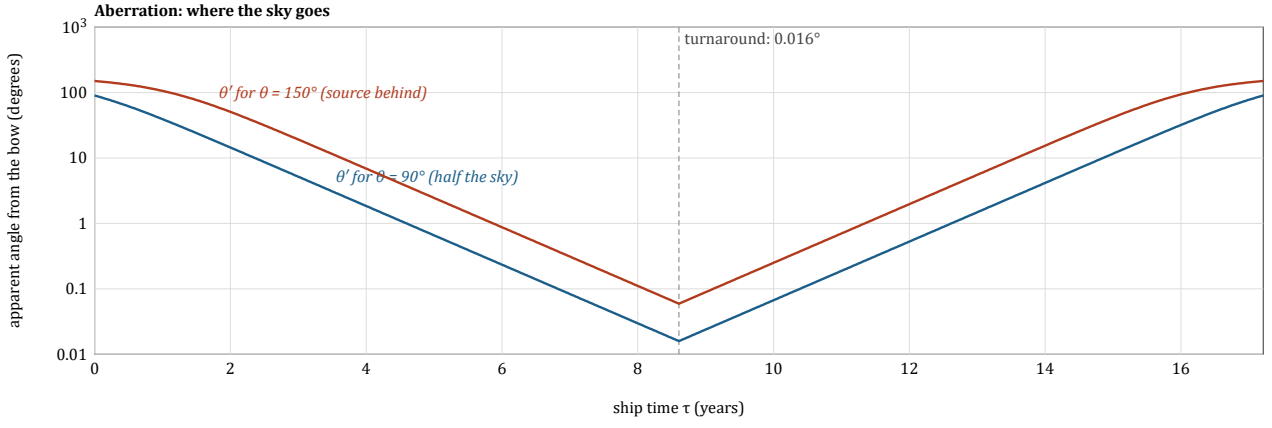


Figure 2. Apparent angle, measured from the bow, of a source that in the Galaxy's frame lies at 90° (the edge of half the sky) and of a source at 150° , almost behind the ship, from equation (10): $\tan(\theta'/2) = e^{-\eta} \tan(\theta/2)$. After 1 year of ship time half the sky already fits within 39° ; after 3 years, within 7° ; at the turnaround, within 0.016° — and the source behind appears 0.06° from the bow.

5. Cosmic microwave background

The CMB is a blackbody at $T_0 = 2.7255$ K [10] in the frame in which it is isotropic. For a moving observer, each direction still presents a blackbody spectrum, with temperature

$$T(\theta) = \frac{T_0}{\gamma(1 - \beta \cos \theta)}, \quad (14)$$

θ measured from the direction of motion [11]. The ship departs from the Solar System, which already moves at 369.82 km/s toward $(l, b) = (264.021^\circ, 48.253^\circ)$ relative to the CMB [10]; the ship's boost is composed with this dipole: the axis and the effective rapidity of the CMB frame as seen from the ship are obtained by composing the two velocities, taking care to compute $\gamma - |\gamma\beta|$ as $e^{-\eta}$ to avoid cancellation. The temperature in a direction d is then $T_0/(e^{-\eta_{\text{eff}}} + \frac{1}{2}|\gamma\beta|_{\text{eff}}|d - \text{axis}|^2)$, where $|d - \text{axis}|^2 = 2(1 - \cos \theta)$ is stable at the apex. At the bow, at turnaround, $T = 19,652$ K.

The radiance of each direction is Planck's law integrated over the visible band with the CIE functions, tabulated at 2,048 temperatures from 300 to 50,000 K on a logarithmic scale. The optical spot is integrated over the area of each pixel with 4-point Gauss quadrature and adaptive subdivision (up to six levels) of the core, whose angular width $\sim 2e^{-\eta}$ rad is compared with the pixel independently of resolution; thus an apex smaller than a pixel conserves its energy when it crosses the boundary between pixels or when the resolution changes. Below a 300 K peak the visible tail is less than $10^{-22} \text{ W m}^{-2} \text{ sr}^{-1}$ and the spot is not computed. The result is summed in 32-bit floating point before the compression (13) and is *not* attenuated by the dust of the Pillars, which is transparent to microwaves in the dust's frame.

The irradiance on a plate facing the bow, $\int \sigma T(\theta)^4 / \pi \cos \theta \, d\Omega$ over the forward hemisphere, is tabulated in η with logarithmic steps in θ (the hot cone has a width of $\sim 1/\gamma$): it equals $\sigma T_0^4 = 3.1 \times 10^{-6} \text{ W/m}^2$ at rest and tends to $(16/3)\gamma^2 \sigma T_0^4$, the T^{0x} component of the transformed radiation; at turnaround it is 217 W/m^2 , and both limits are verified in a test. Table 2 gives the temperature milestones; the same irradiance, converted by the visible fraction of the blackbody, lights the cabin (5.4% of visible sunlight at turnaround).

Table 2. Temperature of the cosmic background at the bow over the course of the voyage.

Temperature at the bow	First crossing (ship years)	Total time above the value (years)
300 K (start of the optical calculation)	4.55	8.11
1,000 K	5.72	5.77
2,000 K	6.39	4.43
5,000 K	7.28	2.65
10,000 K	7.95	1.31
19,652 K (peak, turnaround)	8.61	—

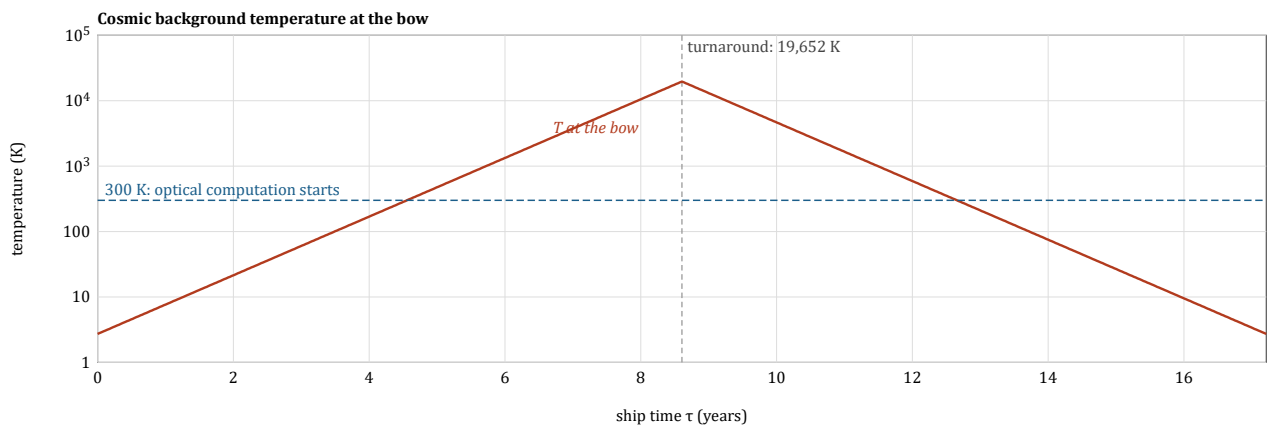


Figure 3. Blackbody temperature of the cosmic background toward the bow, $T = T_0 e^{\eta}$ (corrected for the solar dipole), from equation (14): it rises by a factor e every 0.97 year of ship time, passes 300 K at 4.55 years — when the optical patch starts being computed — and reaches 19,652 K at the turnaround, falling symmetrically while braking.

6. Eagle Nebula: data and reconstruction

6.1 Data

The geometry in the plane of the sky comes from two public photographs [12, 13]: ESO0926a (32′ wide field, B, V and R filters, CC BY 4.0) provides the wide-field structure; Hubble heic1501a (the Pillars, CC BY 4.0), registered to the former by correlation (35° rotation), contributes the structures smaller than 0.08 ly. The directions of the NGC 6611 stars come from SIMBAD and were checked, in arcseconds, against the WCS of the ESO image; temperatures (32,000–41,500 K) and luminosities of eight systems come from Table 5 of Sana et al. [14], with unresolved binaries treated as a single source. The ratios of fifteen optical lines relative to $H\beta$ ($H\alpha/H\beta = 4.343$) come from the example spectrum of McLeod et al. [15], obtained with MUSE, and the $H\alpha$ emissivity uses the recombination coefficient $3.56 \times 10^{-25} \text{ erg cm}^3 \text{ s}^{-1}$, checked against the relation between emission measure and Rayleigh brightness. The depth comes from a reference mesh for 3D printing (NASA/STScI), scaled by 1.725 to match the registered silhouette: height of the Pillars 8.625 ly, box of $6.39 \times 10.53 \times 9.81$ ly, grid of $142 \times 234 \times 218$ cells. All transverse dimensions are measured angles times the adopted distance, 7,000 ly to the center of M16 and 6,992 ly to the plane of the Pillars; the depth is assumed (Section 6.2).

6.2 Transport model

The outreach enhancement of the photographs is undone by a power law with exponent 2.4 (an assumption), and the resulting image is decomposed into an emission envelope (soft maximum at 0.7 ly) and a photographic optical depth up to $\tau_f = 4.5$, converted into the optical depth adopted by the model by

$\tau_v = \min[8, \tau_f(1 + 2.6 \tau_f)]$ — a declared rule, not an independent measurement. The layers are sheets with thickness: the recombination emission in a sheet centered 15 ly behind the plane of the Pillars ($\sigma = 3$ ly, 2% floor), the bands and the parent cloud at 8.5 ly ($\sigma = 2$ ly), the cluster stars in a common plane 3.2 ly behind the plane of the Pillars. Light seen over an absorber is treated as a veil emitted in a layer 0.1 to 1.4 ly in front of it, with the background spectrum. The scattering of starlight uses an albedo of 0.5 and a Henyey–Greenstein phase function with $g = 0.6$; the opacity is $\kappa = 6 \text{ ly}^{-1}$; the scattered continuum is a blackbody of 37,755 K. The absolute brightness is fixed by a single emission measure, $10^5 \text{ cm}^{-6} \cdot \text{ly}$ ($\approx 100 \text{ e}^-/\text{cm}^3$ over 10 ly), a plausible value on the high side.

The transport is a ray march in the rest frame of the nebula, with 224 samples (24 in front, 160 in the fine interval of the bands and the Pillars, 40 behind): line emission, scattered continuum and gray absorption are integrated in order along the ray; the radiance is transformed by Doppler and aberration at the end (the lines shifted by λ/D leave the visible band on approach — H α , at 656 nm, is at 234 nm at 77% of c); besides the premultiplied radiance, the pass stores the exit depth (encoded as $\log_2(1 + d)/34$, the same as in the star pass) and the cumulative optical depth at four points, so that the stars behind the material are attenuated by what actually lies in front of them. The texture level of detail is chosen by rest-frame angle per apparent pixel, which grows with the Doppler factor: the nebula never gains more angular detail than the photographic plane has, nor does it alias when distant. The adopted volumetric distribution is not uniquely determined by the observations: spectroscopy provides constraints on velocities, electron density, extinction and the relative geometry of the Pillars [15], but does not establish the complete three-dimensional field of density and emissivity used here; the positions and thicknesses of the layers, the common plane of the stars and the depth assigned to the mesh are documented assumptions of the model. Section 11 summarizes what in this model is assumption.

7. Propulsion, energy and the flux on the shield

7.1 Photon rocket

A perfect photon rocket is adopted: all the fuel mass is converted into radiation collimated in the direction opposite to the thrust. For this propulsion system the relativistic rocket equation gives $m(\tau) = m_{\text{fim}} e^{b_{\text{fim}} - b(\tau)}$, where b is the rapidity accumulated by thrust, (3): $b = b_1 + \eta - \eta_1$ during acceleration and $b = b_F + \eta_F - \eta$ during braking, with $b_F = b_1 + \eta_F - \eta_1$ and $b_1 = 2.83 \times 10^{-3}$ the burn of the ascent. With a dry mass $m_{\text{fim}} = 100 \text{ t}$:

$$m_0 = m_{\text{fim}} e^{b_{\text{fim}}} = 5.20 \times 10^9 \text{ t}, \quad E_{\text{comb}} = m_{\text{fim}} (e^{b_{\text{fim}}} - 1) c^2 = 4.68 \times 10^{29} \text{ J}, \quad (15)$$

which is what the Sun emits in 1,221 s. The beam power, in the ship's instantaneous frame, is $P = m \cdot a_{\text{thr}} \cdot c$. At the start of liftoff, with a thrust of 1.1 g, it is approximately $1.68 \times 10^{22} \text{ W}$; for comparison, the reference $P_{\text{ref}} = m g_0 c$ adopted in the model is $1.53 \times 10^{22} \text{ W}$ with the initial mass. During braking at 1 g, the power goes from $2.1 \times 10^{18} \text{ W}$ at turnaround to $2.9 \times 10^{14} \text{ W}$ immediately before the stop, when the engine is shut down; during braking the beam points forward relative to the motion. The fraction of fuel used is $(1 - e^{-b})/(1 - e^{-b_{\text{fim}}})$ and the reserve reaches zero exactly at the stop; the systems panel shows the reserve, and the formatting used by the ship radio computes it directly, $e^{-b}(1 - e^{b - b_{\text{fim}}})/(1 - e^{-b_{\text{fim}}})$, so as not to lose the last digits to cancellation, composing the two percentages in integer decimal arithmetic (the sum closes at 100% without rounding the reserve to zero before the end). A collimated beam is not seen from the side in a vacuum without some scattering mechanism; in the interstellar medium, its appearance would depend on the spectrum of the beam and on the properties and distribution of the gas and dust. This scattering is not computed by the simulator; therefore its visual contribution was omitted — there are no plumes or flashes — and braking is indicated by the instruments.

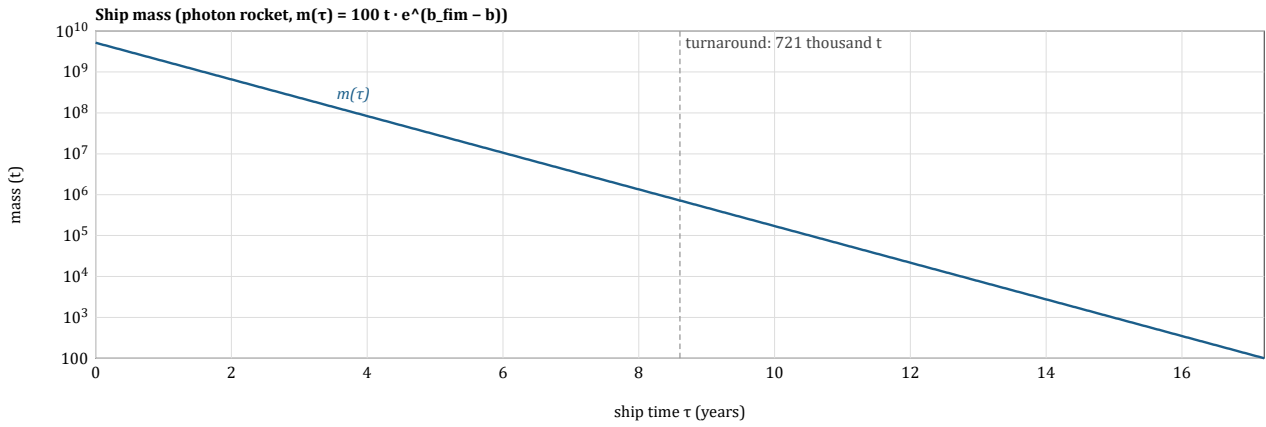


Figure 4. Total mass of the ship along the trip for the ideal photon rocket with 100 t of dry mass: 5.20×10^9 t at departure, 7.21×10^5 t at the turnaround and 100 t at the stop; on a logarithmic scale the curve is a straight line in each leg, because the burn b is the accumulated rapidity itself.

7.2 Interstellar medium and shield

Interstellar gas reaches the bow as a beam of protons with kinetic energy $(\gamma - 1)m_p c^2$, with density γn in the ship's frame. The energy flux on a surface normal to the motion is

$$W = n c m_p c^2 \beta \gamma (\gamma - 1) = n c m_p c^2 \sinh \eta \cdot 2 \sinh^2 \frac{\eta}{2}, \quad (16)$$

written in the second form to avoid $\gamma - 1$ at low speed. With $n = 0.1 \text{ cm}^{-3}$, the Local Bubble density adopted for the whole voyage, $W = 5.9 \times 10^{10} \text{ W/m}^2$ at turnaround (3.4 TeV per proton), about 930 times the emittance of the Sun's surface; the radiative equilibrium temperature of one face, $(W/\sigma)^{1/4}$, is $\sim 32,000 \text{ K}$. The SHIELD block of the systems panel shows these quantities and assumes a shield capable of withstanding them. Semyonov [16, 17] shows that the incoming gas is the dominant radiation source in relativistic flight, above cosmic rays, and that it requires real shielding; the simulation does not model dose, dust erosion or secondary radiation (Section 11).

8. Scenic encounters

8.1 Positions and velocities

On a straight line from Earth to M16 the ship would not pass near any body of the Solar System. So that the voyage would have something to show in the first days, the Moon, Mars, Ceres, Jupiter, Saturn, Uranus, Neptune and Pluto are placed at the point where the ship crosses the mean orbital radius of each, on alternating sides of the route, at 1.5 radii from the center (Saturn at 1.55 R and 0.18 R above the ring plane; Uranus at 1.5 R, through the gap between the first and second bands, with more than 300 km of clearance); Jupiter's moons have real radii (1,821, 1,560 and 2,634 km) at fixed positions, Charon (606 km) lies at (9,000; 5,000; 12,000) km from Pluto — 15,800 km, some 20% less than the real separation of $\sim 19,600$ km — and the asteroid belt is represented by twenty rocks of 20–92 km. The instant of each pass is the physical milestone of the orbital radius (Appendix B), and the speed is that of the trajectory: the displacement per frame is $\gamma \beta c \Delta \tau$ — the Moon's diameter is crossed in 41 s at 307 thousand km/h; Pluto passes at 38.7 million km/h, in 0.22 s. There is no slow motion, gravity assist or perturbation of the route.

8.2 Representation

The bodies are textured spheres (Solar System Scope, CC BY 4.0, with fills for unobserved regions; Pluto from New Horizons with gaps; Ceres fictional) lit from a fixed direction, $\text{normalize}(-0.48, 0.65, -0.90)$, and

not by the Sun — the displayed phase is not the real one. Aberration is applied to the position and angular size of each body, but there is no Doppler color shift nor D^4 gain on the textures: at the planetary passes $\beta \leq 0.036$, which omits up to 3.7% of spectral shift and up to 15.5% of radiance gain (D^4) for a body ahead; in the Oort cloud $\beta = 0.25$, and the factor $D \approx 1.3$ would already nearly triple the radiance. Saturn's rings are synthetic material with bands C (1.275–1.58 R_S), B (1.58–2.018), the Cassini Division (2.018–2.10), A (2.10–2.349) and Encke (2.291–2.297), with $R_S = 58,232$ km in the scene: in kilometers the edges lie at 74,246 (inner C; NASA 74,658), 92,007 (C/B; 91,975), 117,512 (outer B; 117,507), 122,287 (inner A; 122,340) and 136,787 km (outer A; 136,780) — differences of up to 0.55%; what is synthetic is the texture. Uranus's rings are seven scenic bands centered from 1.62 to 2.07 R_U in steps of 0.075 R_U , with widths of 400 to 1,500 km, enlarged for visibility: the real rings are 1 to 10 km wide (the ϵ ring, 20 to 100 km). They have transparency and shadow, with no emission of their own.

8.3 Oort cloud and Local Bubble

From 2,000 AU from the Sun (ship day 90.2, $\beta = 0.25$), a 24-hour stretch of ship time presents nine groups of three icy bodies of 35 to 125 km, with a lunar texture, passing within 4,500 km of the ship between 00:00 and 23:52 ship time; the end of that day ends only the sequence — the model places the exit from the cloud at 100,000 AU, on day 574. The real cloud is inferred, not observed; bodies larger than 1 km lie tens of AU apart, and the probability of passing within 10 thousand kilometers of one of them in 24 hours is essentially zero. The "wall" of filaments of the Local Bubble is a Gaussian transition ($\sigma = 0.003$ ly) at 300 ly, drawn in screen coordinates with fractal noise, without Doppler or aberration; the real bubble is hot gas, invisible in the optical and without a sharp edge, and at 300 ly the ship is already at $\gamma \approx 310$. The heliospheric milestones (termination shock at 90 AU, heliopause at 120 AU, Voyager 1 at 165 AU plus 3.57 AU/year since 2025, Kuiper belt at 40 AU) are rounded values, measured as distance from the Sun.

9. Instruments, ship's log and ship radio

9.1 Panels

All panels are pure functions of the state (Section 2.3), formatted in modules without access to the document and tested in Node. The velocity panel shows the speed in km/h, the fraction of c with at least two significant digits of the difference from 100% (99.9999962% at turnaround), the proper velocity $\gamma\beta c$ in dynamic units (km, thousand km, million km, AU per ship second) and the *rapidity tape*: since η grows at the same rate every ship day, the ship advances along the tape at a constant pace, and the marks at 50%, 90%, 99%, ... 99.99999% of c , at $\eta = \frac{1}{2} \ln((2 - \epsilon)/\epsilon)$, are nearly equidistant. The time panel shows Earth's lead, $t_\oplus - \tau$, on a 1-2-5 full-scale range with a dynamic unit starting from picoseconds (below that, the difference lies under the resolution of the integration in the first seconds) and the factor γ on a logarithmic scale; the mass, also on a logarithmic scale, is on the "Mass and fuel" panel, next to the reserve. The navigation map has a 64 s cycle: 10 s in the overview, 2 s of zoom-in, 50 s in the local view and 2 s of return, with the ship continuing to move along the ruler during the transitions. The overview maps the position by $X = \frac{1}{2} \ln(1 + k u)/\ln(1 + k)$ before turnaround, with $u = (r - R_\oplus)/(r_F - R_\oplus)$ and $k = 10^{12}$, and by $X = 1 - \frac{1}{2} \ln(1 + k w)/\ln(1 + k)$ afterward, with $w = (D - r)/(D - r_F)$ evaluated by (8): the ruler switches from distance covered to distance remaining at turnaround, and both the first kilometers and the last light-years remain visible; Earth and Pluto are fixed references of the Solar System, with the next encounter highlighted. The local view shows two milestones — the previous one and the next one, with distances rounded in the displayed unit and priority given to encounters — and, when the milestone is far away, a rounded absolute reference with local increments, so that the motion remains perceptible; the lower readings differ between the two views, and the on-board distance to the stopping point is the remaining

distance divided by γ . The radiation panel plots λB_λ normalized to its own peak for the Sun astern and the CMB at the bow, and compares, on an energy bar, the solar irradiance $L_\odot/(4\pi d^2) \cdot D^2$ with the CMB irradiance at the bow (Section 5): the cosmic background overtakes the Sun before the first ship year; at turnaround it is 217 W/m^2 against $5.4 \times 10^{-22} \text{ W/m}^2$ from the Sun astern — a factor of $\approx 4 \times 10^{23}$ — and, at arrival, with the ship at rest, $\approx 5 \times 10^8$. The rear camera composes Earth or the Sun with the emission date, the light age and the slow-motion factor (9); the front window and the rear camera are updated at 10 and 5 Hz during cruise.

9.2 Cabin light

The cabin is a single image with three computed light layers: a circadian cycle (day from 07 h to 19 h, night from 22 h to 05 h at 55% with a warm tint, ramps between them), applied multiplicatively; the light entering through the window, applied additively — the sum of Earth's daylight during the ascent ($0.15 \cdot e^{-h/8,500 \text{ m}}$) and the CMB irradiance converted by the visible fraction of the blackbody at the bow temperature and normalized by 550 W/m^2 , which gives 0.32% of visible sunlight at 7 years and 5.37% at turnaround (a lighting approximation: the CMB temperature varies with direction, and the coefficient uses the temperature at the bow); and a glass reflection, whose opacity $0.09 \cdot \text{level}/(1 + \text{outside light}/0.005)$ gives way when there is light from outside. The builder's plate and the cabin shadows follow these layers; there is no calibrated photometry.

9.3 Ship's log and radio

The ship's log is generated by milestone modules that receive the state function and a bisection solver: each milestone (escape, orbits, 1 light-day, heliopause, Oort, CMB temperatures, aberration half-angle, "+100 years on Earth", reference stars such as Proxima, Sirius, Vega and Betelgeuse, speed thresholds, turnaround, arrival) is a computed instant τ , not written by hand, and 108 context facts accompany the milestones, with their sources noted in the code. The ship radio is a news strip with 2,415 prewritten lines (241 original and 2,174 from an expansion), in three voices — Borealis and two fictional employees, Brenda, from the Compliance and Asset Integrity Office, and Gary, from Operational Support and Contingencies. The catalog comments follow an editorial restriction on digits, with exceptions for "1 g" and "24 h/24 hours"; the parser also preserves the ship's approved motto. Numbers written out in words are allowed in administrative humor, but not to introduce physical data. The values in the bulletins come from the simulation; editorial review and tests verify that the comments neither invent readings or failures nor contradict the milestones. The distribution is deterministic: each line has a flight phase and a subject, is selected by the previous or next milestone and by proximity windows, is not repeated within 15 min (history of the last 24), and character replies expire after 5 min or when the phase changes; messages that have become outdated are discarded. There is no real-time AI text generation.

10. Implementation and numerical robustness

10.1 Architecture

The application is static: HTML, CSS, JavaScript (ES modules) and WebGL2, with no runtime libraries. The state function (Section 2) is pure and deterministic; the frame loop reads the clock, computes the state and updates the panels, the sky, the rear camera and the radio. The sky uses an HDR point pass (stars, with a Gaussian PSF and a physical disk when resolved), a background pass (diffuse Milky Way, Earth, atmosphere), a volumetric pass for the nebula (half resolution until the Pillars occupy more than 40 px) and a final compositing pass that adds the CMB in 32 bits and applies (13). Frame rates are chosen by

phase: 60 Hz in close passes, 30 Hz in the first two days, 10 Hz during cruise (5 Hz for the rear camera), because during cruise nothing changes on the scale of a frame.

10.2 Stable formulations

Several quantities of the voyage have ratios of order 10^7 – 10^{19} between departure and turnaround, and double precision ($2^{-52} \approx 2.2 \times 10^{-16}$) is not enough for the naive forms. The choices:

- **Rapidity as the state variable.** η is linear in τ (5); β , γ and $\varepsilon = 1 - \beta$ are derived from it: $\varepsilon = 2/(e^{2\eta} + 1)$ avoids the cancellation in $1 - \tanh \eta$ (which saturates at 10^{-16}) and represents much smaller values, within the limits of floating point. At turnaround $\varepsilon = 3.84 \times 10^{-8}$: the speed is 41.5 km/h short of c , and this number is displayed with two significant digits.
- **Remaining distance.** $D - r$ would lose the last kilometers of 6.6×10^{19} m (at that magnitude the spacing between doubles is 8,192 m); braking uses (8), which goes to zero continuously, and the route map converts to kilometers from it.
- **Differences of hyperbolic functions.** (6) uses the product-to-sum identities instead of $\cosh \eta - \cosh \eta_1$, which would lose digits at the start of phase 2.
- **Doppler and aberration.** (10) and (11) never form $1 - \beta \cos \theta$; the angle is propagated as $\tan(\theta/2)$, with the branches $\sin \theta/(1 + \cos \theta)$ and $(1 - \cos \theta)/\sin \theta$; the limit $\tan(\theta'/2) > 10^{15}$ is treated as $\theta' = \pi$. The composition with the solar dipole computes $\gamma - |\gamma\beta|$ as $e^{-\eta}$.
- **Fuel.** Fractions via $\text{expm1}/\text{exp}$ and the reserve computed directly; in the radio formatting, percentages in decimal integers (BigInt) so that 99.9...% and 0.0...1% add up to 100% without rounding the reserve to zero.
- **Cosmic background.** Radiance in a logarithmic table; temperature via $|d - \text{axis}|^2$, stable at the apex; per-pixel integration with flux conservation, subdivision criterion in angular units; summation in 32 bits outside the stars' half-precision *buffer*, which is clamped at 60,000 to avoid overflow.
- **Depth.** Logarithmic encoding $\log_2(1 + d)/34$, with d in light-years, shared between stars and nebula: a range of many orders of magnitude in the same *buffer* — representable range, not resolution; in float32 the term $1 + d$ loses increments below $\sim 10^{-7}$ ly.
- **Clock.** Alignment with the server via HEAD (an estimate, Section 3.1); T_0 and the times are integer milliseconds; $\tau = t - T_0$ is exact in double precision for $\sim 10^5$ years.

10.3 Verification

The repository includes 128 automated tests in 19 files (Node.js), run on every change, and two in-browser verification pages (806 checks of the route map and 2,804 of the radio texts). Among the physical tests: the CMB irradiance against its two analytic limits; the $H\alpha$ emissivity against the emission measure–Rayleigh relation; the stop with $v = 0$ and total burn at τ_{fim} ; the speed at the passes (displacement = $\gamma\beta c \Delta\tau$); the stability of the CMB after one simulated hour and its independence from history; the absence of an artificial peak astern; the image of Earth in the rear camera; and a CPU replica of the point shader over the 109,400 HYG stars, which pins down the magnitude limit at rest (grouped by the integer part of the magnitude: every star down to mag 7 visible; 30–60% of those of mag 8; none of mag 9; 50,000–62,000 visible over the whole sky), the white color of Sirius, the increase in stars ahead after 1 ship year, the predominance of shifted cool stars at 3 years and the 1° ring with 300–2,000 stars at turnaround. The cleanup of version 1.0 was checked by a pixel-by-pixel comparison of a frozen state (0.03% of pixels different, only digits that change with the clock). The numbers in this section refer to site version 1.1.0, of 19 Oct 2026: the tests run with `node --test check-*.mjs` in the `hybrid/` folder, and the verification pages open in the browser (`check-route.html`, `check-radio.html`); the sources of the data and of the mesh, with

the file hashes, are on the "Sources and credits" page. These tests verify internal consistency with the model; they are not observational validation — passing them neither calibrates the photographs nor demonstrates that a human eye would see that brightness.

10.4 Publication and real time

The site is published as static files; publication stamps the version, a build identifier and the instant $T_0 = 1792422000000$ ms (Unix epoch), which is sealed: every later publication repeats the same T_0 , and the time shortcuts used in development are ignored in the published copy. The instant is the same for all visitors; the displayed state is the state function evaluated at the real clock.

11. Limitations and known problems

The simplifications are listed for the public on the "Poetic licence" page; here they are organized by type, with what is known about their size.

11.1 Acknowledged impossibilities

- **Propulsion.** No perfect photon rocket exists. The mass ratio of 5.2×10^7 for 100 t of total dry mass, and the power of 1.68×10^{22} W at departure, are beyond any known engineering. In a simplified model with a constant fraction $1 - f$ of the lost mass-energy emitted as collimated photons, and the remainder escaping isotropically in the ship's instantaneous frame, the mass ratio is $e^{b_{\text{fim}}/(1-f)}$: as a hypothetical example, an efficiency of 50% raises the ratio from 5.2×10^7 to 2.7×10^{15} — this percentage does not represent a universal efficiency of antimatter engines. The mass of tanks, radiators and reserve is zero.
- **Shield and crew.** A flux of 5.9×10^{10} W/m² ($n = 0.1$ cm⁻³) with no effect on the ship; dose, grain erosion, secondary radiation and ionization not modeled; instantaneous turnaround; uninterrupted 1 g after the ascent, during acceleration and braking (zero at the stop); no life support.
- **Launch.** Vertical ascent with no atmosphere, drag, rotation (465 m/s) or orbital motion of Earth (29.8 km/s), and no parking orbit; departing from a 400 km orbit would change the fuel by 0.008% and the ship time by 41 min. The direction of the ascent is that of the route, which would require M16 at the zenith of the base at T_0 ; at noon on 19 October 2026 it was $\sim 30^\circ$ high at that longitude, and the fixed visual orientation of Earth hides the difference.

11.2 Limits of the data

- **Distance.** 7,000 ly to the center of M16 is the classic value; Gaia DR2 parallaxes give $1,740 \pm 130$ pc $\approx 5,700 \pm 400$ ly for NGC 6611 [18]. The difference changes the ship time little ($17.2 \rightarrow 16.8$ years, through the logarithm in (7)), but changes the Earth time by $\sim 1,300$ years and scales all dimensions of the nebula (height of the Pillars $8.6 \rightarrow 7.0$ ly).
- **Nebula.** All of the depth is assumption: sheets, common plane of the stars, enhancement exponent, $\tau_f \rightarrow \tau_v$ conversion, albedo, g , κ , a single emission measure; only eight of the ~ 500 stars of the cluster illuminate the gas; a line spectrum from a single point, optical only; no multiple scattering; the nebula is shown as in the photographs — light emitted $\sim 6,992$ years before 2026, at the adopted distance —, whereas at arrival, 6,987 Earth years after departure, the ship receives light emitted ~ 7 years before that instant: between the two observed epochs lie $\sim 14,000$ years of unmodeled evolution. At the measured photoevaporation rate (McLeod et al. [15]: $\sim 70 M_\odot/\text{Myr}$, lifetime ~ 3 Myr) the change would be small. The suggestion of a recent supernova based on Spitzer data [19] is a hypothesis popularized in outreach; the Hubble images of 1995 and 2014 [13] record only small changes in the Pillars.

- **Catalogs.** 299,858 stars against billions in reality; the faint and distant ones are missing, especially those that aberration would bring into the window near M16; the Gaia supplement has no velocities (it stays fixed) and was selected with an earlier route axis, 0.1° off the current one; temperatures from color or class, spectra without lines.
- **Dust.** A smooth disk model (12), without the real clouds in the direction of Serpens/Aquila; the diffuse Milky Way and the external galaxies are synthetic.
- **Motion of M16.** No Sun-cluster relative velocity; the scale of what is ignored is 0.024 ly over 7,000 years per km/s.

11.3 Scene choices

- **Encounters.** Planets placed at the crossing of the orbital radius, on alternating sides, at 1.5 radii; lighting from a fixed direction (phase not real); no color Doppler or radiance gain on the planets (up to 3.7% in frequency and 15.5% in radiance with $\beta \leq 0.036$; in the Oort cloud, $\beta = 0.25$ and $D \approx 1.3$ would nearly triple the brightness); synthetic Saturn rings, with edges within 0.55% of the real ones; Uranus rings with bands 400–1,500 km wide against 1–10 km in reality; Jupiter's moons fixed; Charon ~20% closer to Pluto than in reality; twenty rocks as the asteroid belt; Oort cloud with nine invented groups in 24 h (real frequency ≈ 0); the "wall" of the Local Bubble at 300 ly, artistic.
- **Earth.** Blue Marble map from 2004 with historical clouds; the displayed Earth does not rotate (meridian and terminator of T_0); no weather, seasons or city lights.
- **Cabin and perception.** A single image with light layers; no sound, vibration or weight; a fixed-exposure camera, with no eye adaptation and no photometric calibration of the monitor; the glass reflection is a visual layer, not an optical simulation.
- **Narrative.** The ship, the base, the plate and the ship radio (2,415 lines, fictional characters, no invented readings or failures) are fiction; the company is real.

11.4 Known internal inconsistencies

- The density of the medium in the shield calculation is 0.1 cm^{-3} for the whole voyage, while the estimate of the scattered brightness of the exhaust uses 1 cm^{-3} along the route and 100 cm^{-3} in the cavity of M16; inside the heliosphere the value is different again. The heat on the shield varies by a factor of 10 depending on the choice.
- The solar luminosity appears as $3.83 \times 10^{26} \text{ W}$ in the units of the energy panel and as $3.828 \times 10^{26} \text{ W}$ in the milestones (0.05%).
- The ship's log texts call the end point "arrival at the Pillars", while the map calls it the stop, 6.9 ly from the nearest face.

11.5 Model assumptions and sensitivity

- The equilibrium temperature of the shield uses radiation from one face; with two faces it would be $2^{-1/4}$ (16%) lower.
- The inverted photographic enhancement (exponent 2.4), the mesh factor 1.725, the cap $\tau_v \leq 8$ and the $142 \times 234 \times 218$ grid are documented design choices, not measurements; changing them changes the appearance of the nebula without contradicting any data.

12. Conclusion

Borealis Horizon shows that a relativistic voyage can be presented to the public with the right numbers, in real time, for 17 years, with code that fits in a browser: closed-form kinematics, light transformed direction

by direction, a cosmic background computed from Planck's law and a nebula built from public observations, all under fixed exposure and documented visual choices. The price is the declared simplifications — an engine and a shield that do not exist, a volumetric distribution of the nebula that the observations do not determine by themselves, planets placed where they look good — and this document makes them explicit, with the size of each, so that the reader knows exactly what they are seeing.

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Appendix A. Constants and parameters

Symbol	Value	Use
c	299,792,458 m/s	exact
g_0	9.80665 m/s ²	cruise proper acceleration
year	365.25 d = 31,557,600 s	light-year = 9.4607×10^{15} m; ship calendar
AU	$1.495978707 \times 10^{11}$ m	proper velocity, milestones
$R_\oplus$	6,371 km	$GM = g_0 R_\oplus^2$
T_0 (CMB)	2.7255 K	monopole
solar dipole	369.82 km/s; (l, b) = (264.021°, 48.253°)	composition with the ship's boost
σ	$5.670374419 \times 10^{-8}$ W m ⁻² K ⁻⁴	irradiance, shield
$m_p c^2$	$1.50327759 \times 10^{-10}$ J (938.27 MeV)	flux on the shield
n	0.1 cm ⁻³	density of the medium (shield)
m_{fim}	100 t	dry mass
D, distances	7,000 ly (center of M16); 6,992 ly (plane of the Pillars); 6,985 ly (stopping point)	route
route direction	l = 16.890922°, b = 0.753177°	upper third of the Pillars
dust	K = 5.1×10^{-4} ly ⁻¹ ; H = 330 ly; $z_O = 65$ ly; channels (-0.18, 0, 0.30)	extinction
exposure	$E_{\text{dark}} = 5,400$ at 1,200 px/rad; $\sigma_{\text{PSF}} = \max(0.55 \text{ px}, 1.2 \times 10^{-4} \text{ rad})$	sky
nebula	scale 1.725; sheets 15 ly (σ 3), 8.5 ly (σ 2), stars 3.2 ly; $\tau_v = \tau_f(1 + 2.6\tau_f)$; albedo 0.5; g = 0.6; $\kappa = 6 \text{ ly}^{-1}$; 224 samples	transport

Optical depth of (12) along a segment of length d between heights z_0 and z_1 (measured from the plane): $\tau = K d e^{-|z|/H}$ if $|z_1 - z_0| < 10^{-3} d$, and otherwise $\tau = (K d / \Delta z) [\text{sgn}(z_1) H (1 - e^{-|z_1|/H}) - \text{sgn}(z_0) H (1 - e^{-|z_0|/H})]$.

Appendix B. Milestones of the voyage

Milestone	Ship time	State
Escape from Earth's gravity ($v^2 = 2GM/r$)	44 min	ascent at 0.1–1 g net
Moon (orbital radius)	2.98 h	307 thousand km/h; 41 s to cross the diameter
End of ascent (start of the closed form)	24 h	34.9×10^6 km; 827 km/s
Mars · Ceres · Jupiter	2.19 · 3.27 · 4.59 d	scenic passes at 1.5 radii
Saturn · Uranus · Neptune · Pluto	6.25 · 8.87 · 11.1 · 12.7 d	Pluto at 38.7×10^6 km/h
Oort cloud (2,000 AU)	90.2 d	$\beta = 0.25$; model exit (100,000 AU) on day 574
Local Bubble (300 ly)	6.23 years	$\gamma \approx 310$
CMB at 1,000 K at the bow	5.72 years	Table 2
Turnaround	8.606 years	$\gamma = 3,606$; 3,493 years on Earth; 3,492.5 ly
Stopping point	17.211 years	6,985 ly; 6,987 years on Earth; $v = 0$; zero fuel

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