Computer Simulation, Cosmomedia, and Cosmic Imagination

The Cosmic Cognitive Revolution of Space Aesthetics as a Practice of 'Techno-Poetics'

This project introduces techno-poetics as a novel framework for Human-Computer Interaction (HCI), situating computational cosmology and aesthetic imagination within a shared epistemic infrastructure. Through empirical studies of NASA's exoplanet visualizations, JWST renderings, and cosmic sonification systems, it examines how algorithmic media reconfigure human perception of the universe. Departing from conventional usability or visualization paradigms, this research treats simulation as a techno-poetic actant performative interface that generates rather than represents reality. By combining experimental user studies (e.g., TRAPPIST-1 visualization) with philosophical analysis of cosmotechnics and autopoiesis, the project proposes a cosmopoetic HCI paradigm where human-machine collaboration becomes a site of cognitive, cultural, and ethical negotiation. The ultimate aim is to design interaction systems that treat data not as representation but as material for embodied epistemic creation of a shift from designing for understanding to designing as cosmic understanding.

Keywords: Computer Simulation, Cosmomedia, Techno-Poetics, Autopoiesis

Introduction

The James Webb Space Telescope's (JWST) chromatic renderings of cosmic phenomena neither raw sensor data nor artistic abstractions but algorithmically mediated epistemes expose a fundamental tension in HCI: how computational interfaces simultaneously construct and constrain cosmic imagination. Where public discourse celebrated these images as transcendent art, e.g., social media's Van Gogh comparisons, scientists critiqued their metaphorical reductions of multidimensional astrophysical data, which is a dissonance revealing simulations as boundary objects that negotiate between GPU-driven precision and culturally embedded schemas. This paper advances techno-poetic interaction design as a framework to reconcile these poles, positioning JWST's visualizations as Autopoietic interfaces where rendering algorithms recursively adapt to human interpretation patterns. The analysis also focus on cosmomedia infrastructures transforming spectral data into cross-modal cognition, e.g., gravitational wave sonification's embodied learning and operational aesthetics that reframe 'accuracy' as generative efficacy within participatory networks. By analyzing NASA's lunar VR training systems and IllustrisTNG's galaxy simulations, this paper demonstrate how HCI can bridge scientific rigor and public engagement through embodied computational epistemology, where algorithmic processes and human perception co-constitute cosmic meaning.

This paper bridges Space Aesthetics and related Aerospace Design as 'techno-poetics,' a novel interactive epistemic infrastructure that bridges the operative realism between computational cosmology, interplanetary interaction and aesthetic imagination, fundamentally reinterpreting human-algorithm co-creation in scientific visualization. By interrogating digital ethics in cosmic representation, it exposes the blind spot in current discourse, the unexamined symbiosis between simulation epistemology and poetic freedom. The study pioneers 'techno-poetics' fundamentally redefines space aesthetics and interactive visualization from static representation to dynamic, technologically-mediated cognition for future HCI systems operating in creative-scientific domains. The epistemological foundation of techno-poetics, which frames algorithmic iteration as a co-creative process of meaning-making through transmodal interfaces remains underrecognized among many interaction designers who still predominantly adopt instrumentalist paradigms of human-computer interaction. This gap stems from designers' overemphasis on aesthetic form and functional usability, neglecting the poietic potential of computational systems to reconfigure human perception of cosmic phenomena, e.g., transforming sonified dark matter into haptic feedback, should be embedded in interaction logic as an active process, where computational mediation dynamically reshapes sensory inputs to alter embodied cognition of cosmic scales. By treating simulations as meaning-generating practices rather than representational tools, while revealing how similarity logic in computational modeling morphs into creative driving force.

The TRAPPIST-1 visualization study conducted in this paper empirically validates the techno-poetic tension in cosmomedia, demonstrating how exoplanet renderings oscillate between spectral data fidelity (scientific credibility) and aesthetic stylization (public engagement), with mixed-methods evidence revealing an inverse correlation between perceived accuracy and emotional resonance, a quintessential HCI challenge in scientific representation systems containing the measurable tension between data accuracy and public appeal in cosmic representations.

Autopoiesis Cosmopoetic Interfaces: Designing Participatory Human-Computer Negotiation for Visualization Systems

Space Aesthetics as Techno-Poetic Practice redefines human-computer interaction by demonstrating how quantum simulations mediate participatory between computational precision and embodied poetic interaction, ultimately renegotiating humanity's situated agency with interactive visualization systems facilitate as co-adaptive interfaces where human-algorithmic feedback loops co-create interaction semantics through recursive sense-making[1]. Techno-Poetics in interaction design manifests as a triadic framework focus on transmodal cognitive interfaces; human-machine co-creation where algorithmic iterations become meaning-generating interaction practices; and operational aesthetics that transform quantum data into culturally-situated narratives through GPU-rendered visualization. Algorithmic perception (e.g., pattern recognition, data synthesis) actively shapes interaction design sources transforming raw input into shared mental models where computational agency alters user experience design. This positions digital media as user-responsive autopoietic ecosystems[2] where distributed cognition operates not merely as an instrument but as generative of interaction patterns, a bidirectional coupling where agency is distributed across human-nonhuman actants within iterative design cycles. This emergent paradigm positioning digital media as an user-centered ecosystem with distributed embodied cognition as its irreducible component. The interactive materiality becomes enactive and performative rather than descriptive and representational[3], its execution generates phenomenological experiences that exceed programmerly intentionality through emergent interactivity.[4]

The abstract principles of quantum computing aesthetics find tangible expression and self-organizing principle concretely in NASA's exoplanet visualization pipeline, where adaptive rendering algorithms dynamically reorganize computational resources based on real-time data inputs a quintessential autopoietic behavior in technological systems. NASA's exoplanet renderings[5](Figure 1) constitute scientifically informed interactive visualizations rather than direct observational data, serving as hybrid epistemic-interaction artifacts that mediate between empirical constraints and community co-creation.[6] As techno-poetic constructs, they perform dual interaction modality taxonomies by validating atmospheric scattering parameters against spectroscopic data while generating perceptual accessibility for theoretical entities beyond direct imaging capabilities. The renderings operate as autopoietic boundary objects (Star & Griesemer, 1989)[7], they embody participatory looping effects where scientific models and cultural perceptions co-constitute each other through iterative design processes. By negotiating between mathematical rigor and interactive storytelling, these images also reveal a post-representational interaction paradigm. These adaptive visual interfaces prioritize generative efficacy over correspondence, aligning with Hacking's later skepticism about 'unmasking' constructed truths. When digital artifacts neither pure interventions nor passive representations blur the ontology of scientific objects, NASA's renderings epitomize the constructedness of participatory knowledge, where 'reality' emerges from human-computer co-creation between computation, observation, and collective interaction. Autopoietically preserve atmospheric scattering algorithms despite artistic stylization, cosmotechnical interaction practices reconfigure realism itself as a negotiated design process within techno-participatory networks.

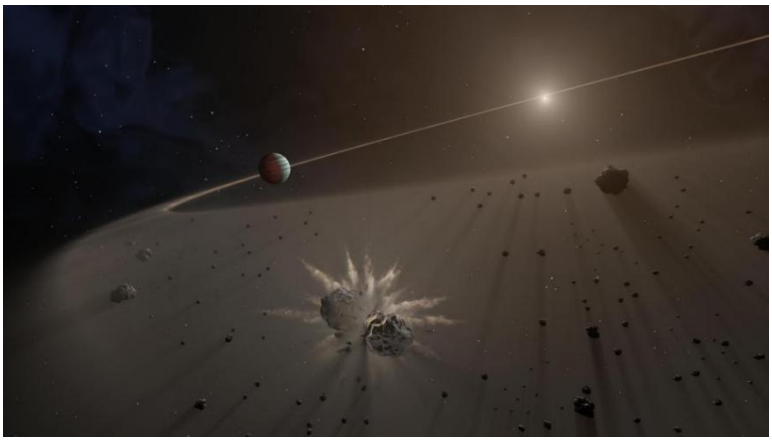


Figure 1 This artist's rendering shows a giant exoplanet causing small bodies to collide in a disk of dust. Source: NASA

Figure 2 Euclid's new image of spiral galaxy NGC 6744. Source: ESA/Euclid/Euclid Consortium/NASA

The concept of techno-poetics in space aesthetics emerges as a computational-humanistic symbiosis between computational cosmology and humanistic imagination, constituting a performative knowledge construction where scientific modeling and artistic creation converge through digital mediation. This paradigm transcends UX objectivity/subjectivity dichotomies by positing cosmic reality as a user-configurable interaction modalities neither pre-given nor purely constructed, but emergent from the entanglement of interaction design patterns, material-semiotic practices, and tangible interaction. Scientific simulations exemplify Whitehead(1979)'s 'creative advance,'[8] where mathematical potentials gain ontological weight through interactive realization, while artistic renderings, e.g., exoplanet visualizations operate as Goodmanian 'affordance-based systems,'(Lopes, 2011) [9]transforming data into interaction flows. Heidegger(1977)'s Gestell is reconfigured as poetic interaction science, which is a mode of cosmic dwelling where algorithms respond, systems adapt, and humanity shifts from observer to participant in the universe's endless self-rendering. The authenticity of models thus hinges not on correspondence but generative efficacy within technological networks, dissolving boundaries between discovery and invention into a crowdsourced techno-poetic cosmology.

East Asian cosmotechnics proposes an ontological shift grounding technological mediation in Yi Jing's processual cosmology. Yuk Hui(2022)'s cosmomedia[10] conceptualizes cosmotechnical systems as interactive epistemic interfaces that materialize divergent cosmological orders through technological artifacts. Departing from Western media theory's universalist assumptions, it foregrounds how embodied interaction techniques ranging from Chinese oracle bones to contemporary machine learning that encode specific cosmic relations, where qi (氣) or algorithmic logic function as mediators between cosmic principles (理, Li) and human-computer interaction. This framework dismantles the nature/technology dichotomy by positioning media as participatory cosmological interfaces that enact epistemic pluralism. Both cosmomedia and techno-poetics reject techno-determinism by insisting on the co-constitution of technical objects and cosmological imaginaries. This autopoietic-boundary-cosmotechnical triad reconfigures digital media as ecological interfaces where cosmotechnics emerges when these technical processes embed Yijing's transformational logic， where algorithmic iterations become contemporary 'techno-divination' cycles.

This synthesis proposes cosmopoetic interaction continuum, where technology neither masters nor mirrors nature, but performative mediators of cosmological plurality and negotiated materiality. While cosmomedia addresses how cosmic patterns sediment into technical forms, e.g., ritual bronzes, techno-poetics interrogates how such forms interruptive potential into aesthetic-political interventions, thus forming a dialectic of inscription and erasure within cosmotechnical becoming. Calendric systems materialize cosmomedia's cyclical epistemology, where celestial patterns, e.g., Jupiter's 12-year orbit are encoded into earthly technical objects thus collapsing cosmic time into human-scale techno-poetic artifacts that resist homogeneous clock-time. As algorithmic media, e.g., AI lunar calendars reactivate ancient cyclical logics Yijing's 64-hexagram sequences[11], they generate techno-poetic folds (nonlinear moments) where divinatory repetition e.g., oracle

bone prognostication[12] coexists with computational recursion and algorithmic rituality, destabilizing modernity's progress myth. These cosmotechnical deliberations crystallize as boundary objects for HCI design, where the self-organizing dynamics inform adaptive interfaces, ultimately reframing NASA's exoplanet data visualization as a participatory cosmotechnical system. This conceptual network ultimately positions HCI systems as cosmopoetic assemblers neither neutral tools nor deterministic structures, but fractal mediators that simultaneously sustain self-referential operational closure (autopoiesis) and enable cross-epistemic boundary objects.

In 2024, the European Space Agency (ESA)[13] released five new images from the Euclid mission(Figure 2), specifically an artistic concept map of exoplanets, showcasing the prowess of space telescopes in probing two pivotal cosmic enigmas: dark matter and dark energy. The invisible constituent known as 'dark energy' is the mysterious force accelerating the universe's expansion. Scientists advocate for restoring the atmospheric scattering effect based on spectral data, whereas artists argue for incorporating fictional aurora phenomena to bolster visual appeal. The discord between scientific models and artistic renderings transcends mere differences in expression techniques; it encompasses an ontological dispute concerning model realism. Scientific models strive for empirical adequacy, whereas artistic renditions emphasize aesthetic resonance. When simulations produce a 'virtual universe,' their aesthetic output, such as nebula rendering, may influence scientists' intuitive judgments, fostering a circular reasoning loop. This conflict is not merely about expressive disparities but also delves into interactive logic controversy surrounding model authenticity. Manned space training systems, exemplified by NASA's virtual moonwalk simulation through lunar VR training, serve both as technical instruments and generators of aesthetic experiences, profoundly revealing how autopoiesis of computer simulations reconstruct the paradigm structure of scientific cognition.[14]

Figure 3 A screen capture of a virtual reality view during the Artemis III VR Mini-Simulation.
Sourse: Prototype Immersive Technology lab at NASA's Johnson Space Center in Houston.
Figure 4 Test subject crew members execute a moonwalk in the Prototype lmmersive Technology lab at NASA's Johnson Space Center in Houston. Source: NASA/Robert Markowitz

NASA's VR training for Artemis III exemplifies autopoietic cosmopoetic interfaces the self-sustaining systems that co-evolve with human perception to negotiate cosmic scales. Self-generating environments the Nobile Rim 1 lunar site built, once modeled in VR, becomes a dynamic training tool that can continue to be improved through iterative use repersenting as a hallmark of autopoietic systems. Mixed reality integration interacting with real objects while immersed suggests nascent cosmopoetic interfaces, where physical/virtual boundaries blur to reconfigure astronaut perception. At its core lies the embodied cognition framework, wherein proprioceptive feedback mechanisms dynamically negotiate between the physical corporeality of the astronaut and the digital affordances of the simulation environment. This creates a hybrid cognitive space where phenomenological first-person experience becomes the substrate for constructing scientifically verifiable knowledge. Temporally, the simulation achieves what Merleau-Ponty might describe as compressed historicity(de Vaujany & François-Xavier, 2023)[15] collapsing geological epochs into iterative experimental cycle by manipulating lunar timelines in accelerated temporal frames, the simulation reveals patterns of planetary formation. This temporal compression doesn't merely accelerate observation but fundamentally alters our relationship to deep time, making planetary history

experientially available rather than inferentially reconstructed. The most radical shift occurs in phenomenological reduction, where the simulation isolates lunar gravity's sensory signatures from terrestrial perceptual interference. This creates a pure corporeality phenomenological field for studying extraterrestrial embodiment. The astronaut's proprioceptive dissonance under reduced gravity becomes both empirical data and existential revelation, exposing the culturally sedimented assumptions embedded in Earth-bound sensory-motor schemas. The system's aesthetic dimensions (e.g., regolith particle dynamics' visual fidelity) actively shape operational protocols, demonstrating that virtuality doesn't imitate reality but reconfigures it through computational phenomenology. This duality positions VR not as art training tool but as epistemic infrastructure, as cosmomedia in this case, VR transcends traditional mediation by establishing a thirdspace where lunar geology and human proprioception co-evolve in real-time computation, generating hybrid forms of planetary cognition that are neither purely subjective nor objectively verifiable but emerge from their bidirectional coupling.

The VR environment as I observed, though continuously improved, operates within NASA's predefined epistemic boundaries somehow limiting autopoiesis as a self-generating process. Mixed reality interacting with real objects hints at human-computer symbiosis, yet fails to let astronauts co-author the virtual cosmos. The system's real applications reveal a paradox that mimics cosmic exploration while reinforcing hierarchical control, undermining the emancipatory potential of autopoietic design. This case does contains critical limitation on lack of fully recursive adaptation, however it embodies autopoietic principles in HCI by creating a self-evolving simulation environment that dynamically reconfigures human perception of lunar exploration through mixed-reality interfaces, though constrained by its instructor-driven framework.

When numerical simulations are neither purely theoretical deductions nor traditional experimental observations akin to the Hubble telescope's galaxy surveys, but rather verifiable virtual realities generated through algorithms, with engineering verification and perception training capabilities, they obscure the boundaries between 'discovery' and 'invention' in traditional science. Consequently, the criteria for determining scientific authenticity shift from 'correspondence theory' to 'generation theory.' This model is grounded in the epistemological foundation of 'model as experiment.' When the visual output of numerical simulations, such as the Euclid telescope's dark matter distribution map, is imparted with aesthetic value, its role as a scientific tool begins to blur. The epistemological tension between scientific modeling and artistic representation has led to the same numerical simulation technology being utilized to predict asteroid impact probabilities and employed by Hollywood to render the ecosystem of Pandora in the movie 'Avatar'(2009). The model's 'authenticity' standard has been fundamentally challenged. Where does the boundary lie between scientific modeling and artistic visualization? The significance of the model is no longer solely determined by its representational function but is realized through operational efficacy in interactive practice. Scientific models belong to denotative symbol systems, with their effectiveness hinging on correspondence with the empirical world. artistic visualizations belong to affordance-based systems, with their worth residing in stimulating flesh perception and imagination rather than precise representation. This division underscores a transition from the crisis of representation to operative realism, where modeling practice in interactive interface has shifted from the 'representational paradigm' to the 'operative-generative paradigm.'

Symmetrical Actants in Cosmic Sensemaking: How Space Probe Interfaces-Algorithmic Visualizations-Embodied Human Perception Co-Construct Gravitational Wave Realities

From the perspective of Bruno Latour's Actor-Network Theory[16], the dynamic interaction scaffolds of simulated universes as interactive systems where mathematical models function as dual-interface agents both representing and actively constituting cosmic reality through iterative optimization. Telescopic observation traditionally presupposed a detached human observer decoding static cosmic 'objects' (Newtonian res extensa), whereas multimodal simulations reframe embodied cognition as a triadic negotiation interface among space probes as material actuators, algorithm models as computational actants, and human observers as perceptual interpreters. They constitute equal 'actant,' as the particle distribution in numerical simulations undergoes iterative optimization, it does not merely passively reflect the universe but co-constructs experiential meaning through interactive feedback loops. Cosmomedia has emerged as a new 'realistic field,' , it is neither purely discovered (realism) nor invented (constructivism), but co-enacted by this hybrid interactive network by

continuously negotiated through human-data interaction. The cosmic phenomenon now is the simulation not as proxy, but as co-constitutive ground. For instance, when gravitational wave data is transformed into acoustic simulations, participants develop embodied understanding through multimodal interaction[17], and abstract theoretical entities obtained my simulation enable tangible interaction modalities, thereby entering the realm of human experience.[18]

When examining the GW190521 event detected in 2019 a black hole with a mass 142 times that of the Sun resulting from the collision of two black holes, the LIGO/Virgo[19] Collaboration integrates data from multiple detectors, eliminates noise sources such as ground vibration and electromagnetic interference, and verifies the signal's authenticity through advanced detection techniques. Through specific algorithmic methods, astronomical data is transformed into audio waves with distinct impact effects. The sensitivity of human hearing to rhythm and pitch renders it an efficacious medium for exploring complex datasets through embodied interaction. Acoustic processing aids scientists in intuitively discerning the temporal structure characteristics of gravitational wave signals. The acoustification of celestial phenomena, such as black holes, has emerged as a groundbreaking interaction modality in scientific communication[20]. Despite the lack of systematic public perception survey data, the participatory engagement phenomenon ignited by NASA's 'Cosmic Sounds' album, released on Halloween in 2017, comprising 24 celestial audio clips, underscores its capacity to effectively pique the public's interest in cosmic phenomena.[21] It is crucial to emphasize that this form of acoustic simulation serves as a interactive knowledge mediation system of allowing live parameter tweaking of cosmic events, rather than strict scientific data. Its pedagogical interaction value resides in establishing a bridge between abstract concepts and multimodal interaction pathways that function as interactive knowledge mediators rather than data replicas, thereby rendering theoretical entities, initially beyond human perception, e.g., black holes, empirically perceivable.

Between 2024-2025, space gravitational wave detectors like LISA and Tianqin Project[22] comprising three satellite-based interferometers (SC1/2/3) are pioneering cosmic soundscape research. FAST's[23] PTA experiments exemplify this trend by converting pulsar timing arrays into generative audio, notably slowing pulsar rotation periods 80× and mapping signal amplitudes to sonic intensity. These initiatives reframe gravitational wave detection as participatory sensing, transforming complex astrophysical data into accessible sonic metaphors for public engagement. Notably, even the percussive and drum-like sounds within the acoustic presentation originate from the frequency characteristics of the pulsars. Transforming gravitational wave detectors into tangible interaction interfaces for cosmic exploration and embodied learning that enabling direct interaction with theoretical physics via multi-sensory feedback. These interactive systems redefine digital media as participatory design spaces where abstract scientific concepts become experientially tangible through participatory meaning-making.

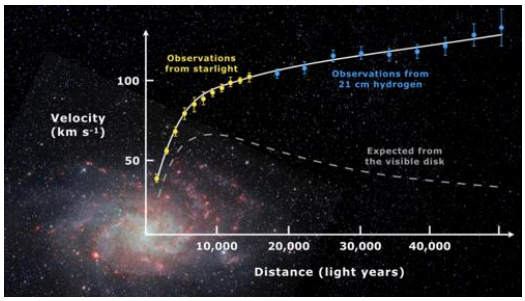
The integration of neuroscience into sonification research elucidates how auditory representations of non-acoustic data (e.g., gravitational waves) leverage cross-modal plasticity in the human brain. Recent studies demonstrate that the superior temporal sulcus (STS) and auditory cortex dynamically remap visual/olfactory inputs into pitch-temporal patterns, mirroring the 57-octave frequency scaling used in cosmological sonification(Zatorre et al., 2005).[24] This aligns with neuroimaging evidence showing that MXene/van der Waals heterostructure synapses can simulate visuo-olfactory integration via spike-timing-dependent plasticity (STDP), suggesting analogous mechanisms may underpin auditory-visual transduction in data sonification. Neuroimaging confirms that cross-modal transduction (e.g., STS remapping) underlies effective design. Memristive neuron models achieve 96.84% accuracy in interactive sensory blending[25], validating techno-poetic interfaces as biologically grounded cognitive tools. Such biological plausibility reinforces sonification's efficacy: when LIGO's ~10^{-15} Hz gravitational waves are compressed into audible ranges(Abbott et al., 2016), they exploit the brain's inherent capacity for multisensory binding a process anatomically localized to the thalamocortical loop.[26] These findings position sonification not merely as a data translation tool, but as a neurocognitively optimized interface for complex information synthesis.

Cosmomedia breaks the boundary between organic matter (human) and inorganic matter (machine), and incorporates 'non-human perceptual entities' such as gravitational wave data into the human experience system. Derrick de Kerckhove's philosophy of digital media points out that media is 'breaking domains'[27], a mechanism for connecting, converting, and

generating dynamic wholes. Intelligent technology reconstructs human senses, and simulations such as acoustic black holes realize the technical extension of hearing, making the inaudible audible. Borrowing the concept of 'field' in physics, digital media constructs a new field of realization, neither a pure physical space nor a virtual space, but a hybrid field that makes theories real through data conversion. This realization process is different from traditional scientific visualization. It creates a more direct cognitive entrance through multi-sensory simulation (especially hearing).

In essence, both the construction of scientific models and the creation of visual narratives employ indirect evidence to elucidate their respective fields. The ΛCDM (Lambda Cold Dark Matter) model (Figure 5)[28], proposed in contemporary cosmology, explains the galaxy rotation curve by presupposing the Navarro-Frenk-White (NFW) density profile of the dark matter halo ($\rho(r) \propto 1/[r(1+r)^2]$). This practice is reminiscent of how the 19th-century astronomer Percival Lowell explained the blurred images of the Martian surface through the geometric lines of the hypothetical 'Mars Canals' (Figure 6), aiming to fill the gap in telescope resolution at that time[29]. These two practices share a profound epistemological structure: models are not merely tools but also extensions of human embodied cognition, transforming unobservable entities (such as Martian landforms and dark matter distribution) into calculable and visual objects. The earliest systematic exposition of this analogy can be traced back to the study titled 'From Quantum Fluctuations to Galaxy Formation,'[30] which highlights that the dark matter 'gravitational glue' hypothesis and Space Aesthetic creation share the thinking tool of visualizing the invisible. The former reconstructs the three-dimensional distribution of the dark halo through numerical simulation, whereas the latter visualizes the Martian landform through sketch lines. The latest analysis, conducted in 2025, further reveals that the cold dark matter parameters of the ΛCDM model and the 'canal' hypothesis belong to the category of explanatory fictional entities.'[31] The 'The universal rotation curve of spiral galaxies'[32] study explicitly compares the parameter calibration process in numerical simulation to 'modern star mapping,' directly citing the example of astronomical mapping in the 19th century to illustrate the aesthetic constructivism of theoretical modeling [33]. The halo particle distribution algorithm adopted by large-scale cosmological projects, such as the Millennium Simulation, essentially continues the tradition of early astronomers filling data gaps through geometric patterns[34]. We are also witnessing the realization process of Whitehead(1979)'s concept of eternal objects in digital media. [35]These potential forms transcend specific time and space (such as mathematical relations and geometric structures) and have obtained new realization paths in digital media, transforming data potential into specific perceptual forms. For instance, the NFW density profile in dark matter simulations was originally a mathematical hypothesis. Paradoxically, through the computational iterations of projects like the Millennium Simulation, it has transformed from a pure mathematical equation into an observable cosmic structure template, gradually becoming a 'reality' recognized by the scientific community.[36] It achieve interaction validity through recursive cross-validation with Chandra's AGN data, not passive mirroring of reality.

Eternal objects do not exist a priori but are 'summoned' in computational practice, which is an interface constantly generated through the interaction of computational practice, observation technology, and theoretical imagination. The the ΛCDM model (Fig. 4) operationalizes Ronald Giere(1988)'s theoretical hypotheses[37] by demonstrating how mathematical abstractions like the NFW density profile transition from formal constructs to ontologically robust entities through recursive computational enactment. Ppredictive coherence across scales, e.g., galactic rotation curves → CMB anisotropies supplants mirroring as the adequacy criterion, which is a process aligning with Giere(1988)'s framework where models derive validity from generative efficacy in predictive networks rather than representational correspondence. The study's techno-poetic implications are equally profound: NFW profile color mappings exemplify how visualization aesthetics shape scientific intuition, blurring boundaries between epistemic rigor and generative emergence. By computationally actualizing dark matter's ontological status from mathematical abstraction to participatory entity, the work underscores simulations as constitutive rather than representational practices in cosmological knowledge production. This operationalizes techno-poetics, where ‘authenticity' derives from recursive human-machine negotiation, not representational fidelity.



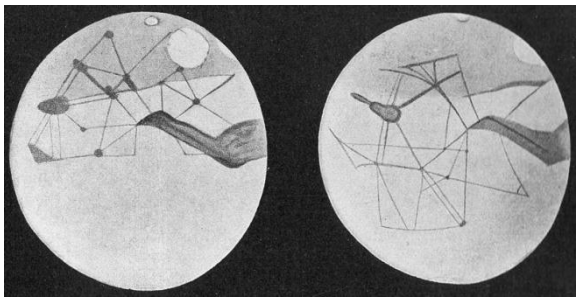


Figure 5 Rotation curve of spiral galaxy Messier 33 and a predicted one from distribution of the visible matter. Source:Stefania Deluca

Figure 6 Martian canals depicted Source: Percival Lowell

While the Mars Canals and ΛCDM simulations both exemplify 'visualizing the invisible,' their epistemic foundations diverge critically. While both use imaginative representations, Lowell's 19th-century Martian canals relied on subjective visual interpretation (later proven wrong), whereas modern dark matter simulations combine supercomputer calculations with multiple independent observations. The key distinction lies in verification: space probes, algorithms, and scientists work together to test ΛCDM predictions against cosmic microwave background data and gravitational lensing, creating a self-correcting system. This collaborative process between human perception and technological actants, where telescopes detect, algorithms interpret, and researchers validate emonstrates how reliable cosmic knowledge emerges from this interactive symmetry of human and non-human contributions.

Interface Ontologies of Designing the Invisible: Systemic Distortion vs. Hyperreal Transcendence

Since the early 20th century, computer simulation has gradually emerged as the pivotal research methodology in the fields of astronomy and aerospace engineering. The critical question is not whether models approximate reality (they inherently do via abstraction), but under what conditions their approximations yield reliable knowledge. Model-worldbuilding coordination via dynamic adequacy posits that scientific models achieve interaction validity not through static correspondence but through their capacity to adaptively mediate between theoretical constructs and empirical constraints in iterative validation cycles. Interactive model validity in their agency affordances to recursively refine world-relations through computational and observational feedback. This process inherently acknowledges the constructive plasticity of models, where their ontological robustness emerges from sustained generative alignment with evolving observational frameworks rather than fixed representational fidelity. The 'dynamic analogy' theory[38] by Weisberg(2013) in his seminal book Simulation and Similarity, posits that scientific models approximate reality by establishing cognitive mappings with the actual world through processes of selective abstraction. The core tenet of this theory underscores the embodied recognition that scientific models are fundamentally cognitive tools constructed via selective abstraction, rather than mere replicas of reality.

Notably, in the Lucy exploration mission, NASA employed a streamlined model to determine the orbit of Trojan asteroids[39], primarily relying on gravitational perturbation theory rather than an analysis of celestial compositions(Olkin et al., 2024). This mission was propelled by the Atlas V-401 rocket, with its orbit design solely necessitating the consideration of the target celestial body's mass distribution and positional parameters[40]. The mission's success hinges critically on the deliberate exclusion of 'irrelevant variables,' like the chemical composition of celestial bodies, thereby enabling the simplification of intricate celestial systems into computable particle system models. An in-depth analysis of dynamic analogy reveals it to be a strategy of cognitive economy. By reducing Trojan asteroids to point-mass gravitational sources, scientists traded local precision for the global viability of multi-body system evolution predictions. The central paradox confronting contemporary celestial mechanics is that the quest for absolutely precise models frequently results in computational infeasibility, whereas overly simplistic models forfeit predictive utility. This contradiction is particularly

pronounced in galactic evolution simulations, where researchers confront a formidable dilemma between particle resolution and simulation scope. As Winsberg has emphasized, the triumph of computer simulation as a 'third paradigm' hinges precisely on scientists' meticulous management of the degree of 'systematic distortion.'(Seel, 2012)[41] It mandates both a robust correspondence with the physical world and the preservation of computational feasibility through systematic distortion. The 'dynamic analogy' theory elucidates the fundamental nature of scientific modeling constructing cognitive mappings through selective abstraction, thereby endowing the model with explanatory and predictive prowess under specified objectives.

Artistic visualization pursues hyperreal effects: a photorealistic CGI face or Borges' 1:1 map obliterates the referent through excess fidelity, generating Baudrillardian(1981) simulacra that 'murder reality'[42]. Scientific distortion is subtractive sacrificing multisensory bandwidth for predictive power, e.g., climate models omitting micro-scale turbulence; In the meanwhile, artistic hyperreality is additive layering idealized details, e.g., Renaissance perspective's 'perfect' geometries until representation implodes into self-referential interfaces, where Platonic solids are systematically decomposed into perspectival constructions that harmonize mathematical rigor with visual illusion.[43] Figure 7 & 8 further reveals the treatise's dialectic, its 'perfect' geometries simultaneously serve as tools for technical control and triggers for aesthetic rupture, mirroring the broader tension between scientific distortion and artistic hyperreality. Yet both share a deeper truth as Latour argues in Science in Action (1987)[44], all modeling is alchemical, transmuting noise into legibility through deliberate interaction constraints. The difference lies in user intentionality, science's distortions aim at control that reduces complexity to find patterns, art's hyperreality at ecstatic subversion by add idealized details until the representation loses touch with reality. Models (whether scientific or artistic) don't just copy reality, they reshape it to serve their purpose. Science trades realism for usefulness, while art pushes realism to the point of becoming its own reality. This antinomy reveals modeling's fundamental aporia: all acts of representation, whether scientific or aesthetic necessitate epistemological violence, yet systematic reduction and hyperreal excess dictates whether we apprehend reality as a determinate system or as an latent interaction patterns.

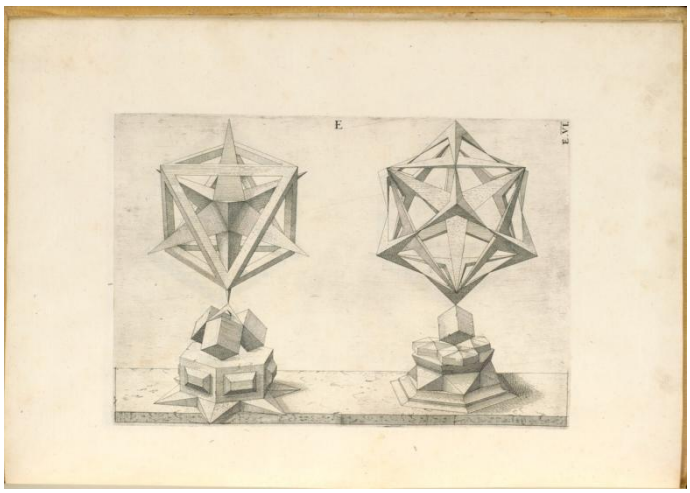


Figure 7 Wenzel Jamnitzer's treatise, Perspectiva Corporum Regularium (Perspective of Regular Solids), published in 1568
Figure 8 Perspectiva Corporum Regularium. Source: Hyperallergic

When IllustrisTNG simulates the evolution of the universe, [45] it fundamentally gives rise to a novel interaction of knowledge generation. Through an intricate and sophisticated mechanism of selective abstraction, IllustrisTNG has formulated a computable model of the universe. This modeling approach distills dark matter into a particle system and transforms intergalactic gas into magnetic fluids, thereby rendering the 13.8 billion-year evolution of the universe computationally tractable. This abstraction process is inherently a manifestation of cognitive economy, it entails a trade-off between local precision (such as the omission of detailed structures smaller than 230 light-years) and the efficacy of

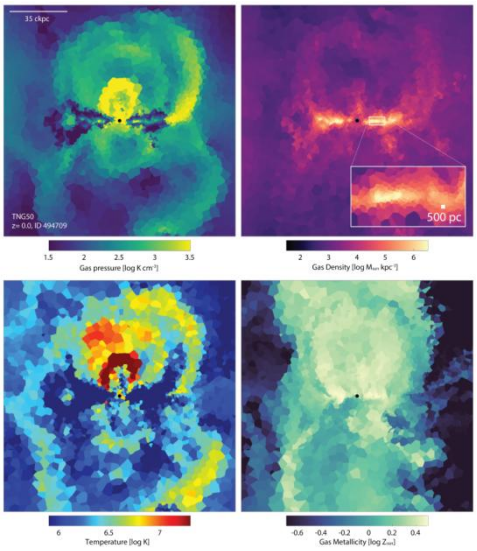
predicting large-scale cosmic structures. Epistemological insights reveal that scientific models are not mere facsimiles of reality, but rather represent selective reconstructions of reality, guided by specific cognitive objectives. The project team's adoption of a hybrid validation paradigm is particularly noteworthy. They cross-validate X-ray observational data (including 8000 active galactic nuclei documented by the Chandra telescope) with simulation outcomes, thereby constructing the first comprehensive evolutionary history of black holes, encompassing both accretion and merger-driven growth. This 'observation-simulation' closed-loop verification system not only mirrors the traits of Weisberg's third-generation scientific paradigm but also underscores the constructive nature of scientific modeling as a cognitive endeavor.

In the IllustrisTNG project, a pioneering endeavor in cosmological simulations, the significance of artists is prominently manifested in the realm of scientific visualization and the reconstruction of co-adaptive interfaces. The quintessential value of this endeavor resides in the transformation of high-dimensional data into cognitive paradigms that are perceptible to humans. Cross-modal data translation facilitates the conversion of physical parameters, such as the distribution of dark matter exemplified by the orange/white structure in the TNG50 simulation and galactic gas depicted as blue shock waves into dynamic images possessing aesthetic structures. This enables the narrative expression of terabytes of computational data per second. Through techniques such as color coding, which involves mapping hydrogen gas flow rates to hues, and sonification, where black hole jet frequencies are translated into audio, a multi-sensory cognitive channel is established.[46] Art further contributes to the design of cognitive infrastructure and the development of mixed reality interfaces, enabling the compression of the universe's 13.7 billion-year timeline, spanning from the Big Bang to the present, into an interactive experience lasting merely 10 minutes.[47] Within this experience, visual metaphors crafted by artists, such as the representation of gravity wells as fluid vortices, significantly diminish the comprehension threshold. In the visualization of TNG50's tidal tail, fractal algorithms were introduced by the artist to accentuate the topological characteristics of the stellar stream, a practice later affirmed to be instrumental in identifying dark matter substructures. When artists deeply engage in the implicit space encoding of cosmic simulations, such as utilizing Generative Adversarial Networks (GANs) to generate plausible galaxy morphologies in unobserved intervals, their work transcends the confines of traditional scientific illustrations, evolving into a meta-modeling interactive practice that bridges computational astrophysics with embodied cognition.

The cosmological simulations IllustrisTNG and Millennium simulation embody fundamentally distinct paradigms of cosmic cognition. Millennium pioneered structural cosmology by modeling dark matter halos as gravitational scaffolding (~10^{10} particles in 500 Mpc/h)[48], prioritizing hierarchical merger trees while relegating baryonic physics to post-processing approximations(G. Mark Voit et al 2024). Millennium's 'dark matter-first' approach treats galaxies as emergent byproducts of halo dynamics, adhering to Weisberg's dynamic analogy through subtractive abstraction. In contrast, IllustrisTNG advances processual cosmology through magnetohydrodynamics (MHD) and integrated baryonic feedback, e.g., AGN jets, stellar winds, resolving galaxy-halo multiuser synchronization at <230 light-year scales. IllustrisTNG's 'baryon-aware'[49] methodology operationalizes Barad(1998)'s 'agential realism', where algorithmic actualization, e.g., GPU-rendered spiral arms co-constitutes cosmic reality through human-techno-material entanglement. While Millennium's particle distributions passively represent cosmic structures, IllustrisTNG's emergent phenomena, e.g., black hole-driven bubbles actively participate in meaning-generation as symmetrical actants. The ontological tension lies in their validation frameworks. Millennium's halo catalogs achieve representational realism through statistical correspondence with large-scale surveys. IllustrisTNG hybridizes operative realism by cross-validating X-ray observations[50], e.g., Chandra's AGN data with simulated galaxy morphologies,[51] blurring discovery and invention dichotomy. Where Millennium exemplifies phenomenological models sacrificing micro-scale accuracy for predictive scope, mathematical potentials, e.g., NFW density profiles gain reality through computational iterativity.

This innovative data processing approach constitutes an epistemological mediation, converting abstract numerical outputs into cognitive constructs that align with human perceptual patterns. Nevertheless, this artistic rendition introduces novel epistemological challenges. When simulated galaxy collision imagery (such as a structural slice depicting a 1.2 billion light-year scale) is juxtaposed with authentic Hubble telescope imagery, it frequently elicits ontological confusion regarding

the essence of the real universe among the general populace. Artistic visualization has emerged as a contentious issue concerning scientific authenticity, as it obfuscates the delineation between simulation and reality, thereby challenging our conventional understanding of scientific representation and interaction.



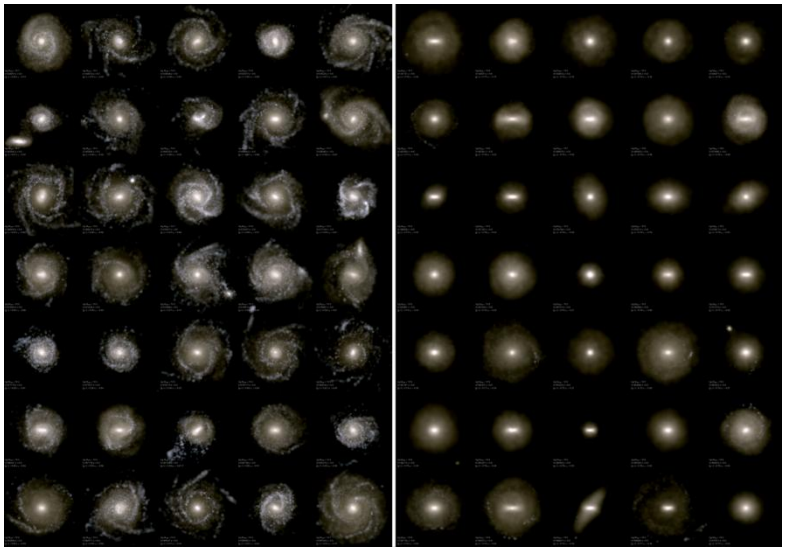


Fig 9 A outflow-driven 'bubble' produced by supermassive black hole feedback

Fig 10 Mock stellar light images of two galaxy samples: blue, star-forming systems Source: tng-project.org

Whether emergent structures in cosmological simulations, e.g., IllustrisTNG's spontaneous galaxy arms constitute epistemic discoveries or algorithmic artifacts, the TNG50(2023) simulation model possesses the capability to spontaneously generate unforeseen cosmic structures, such as the spiral arms of galaxies. This observation suggests that the simulations have indeed encapsulated some fundamental laws governing cosmic evolution. On the other hand, the marked discrepancies between the simulation outcomes and empirical data, exemplified by deviations in radio radiation power, unequivocally highlight the model's limitations. This apparent contradiction gives rise to a fundamental inquiry: Does the simulated universe possess ontological validity? The intricacy of this issue is further underscored by its technical particularities. The computational constraints inherent in supercomputers necessitate the encoding of continuous cosmic principles into discrete mathematical frameworks. This technological mediation raises the question of whether it distorts the inherent continuity of cosmic phenomena. This issue manifests as a profound tension between methodology and ontology and also mirrors the central controversy surrounding 'computational realism' within contemporary philosophical discourse on science. It unveils the fundamental dilemma inherent in scientific modeling, which perpetually oscillates between 'cognitive adaptation' and 'ontological approximation' through systematic distortion. This conflict aptly captures the quintessence of scientific endeavor: scientific models are neither mere instruments nor flawless reflections but rather constrained approximations of reality within specific cognitive paradigms.

This conflict can be analyzed within the theoretical framework posited by Baudrillard(1981)'s simulation theory. When the 'simulation' inherent in scientific modeling converges with the 'simulacrum' of artistic visualization within digital media, we find ourselves immersed in a cognitive state of hyperreality. NASA's renderings of exoplanets, for instance, embody neither purely scientific data nor unadulterated fiction; rather, they represent a synthesis of scientific reality and artistic fiction. These renderings must concurrently meet the rigorous standards of spectral data accuracy and the compelling demands of visual narrative effectiveness. This hybrid state poses a significant challenge to the traditional scientific philosophical construct of 'model authenticity' and compels us to reconsider the applicability of Hacking's 'experimental realism'[52] within the context of interdisciplinary modeling practices in the digital era. The dialectical interplay between scientific modeling and artistic reproduction is evident: scientific models exert cognitive control through abstraction, whereas artistic

visualizations evoke aesthetic experiences through concretization. In the digital technology epoch, the demarcation between these two domains is increasingly blurred, giving rise to a techno-mediated epistemic-aesthetic hybrid.[53] This phenomenon necessitates a reevaluation of the 'authenticity' benchmarks for scientific models and prompts us to ponder what we have always wondered in the very beginning: At the nexus of science and art, does a novel interaction paradigm exist that can accommodate a mode of understanding the universe that is both meticulously precise and imaginative?

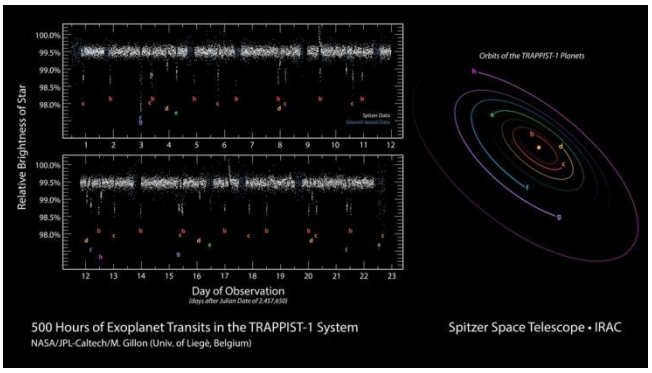
How TRAPPIST-1 Visualizations Mediate Cosmic Understanding

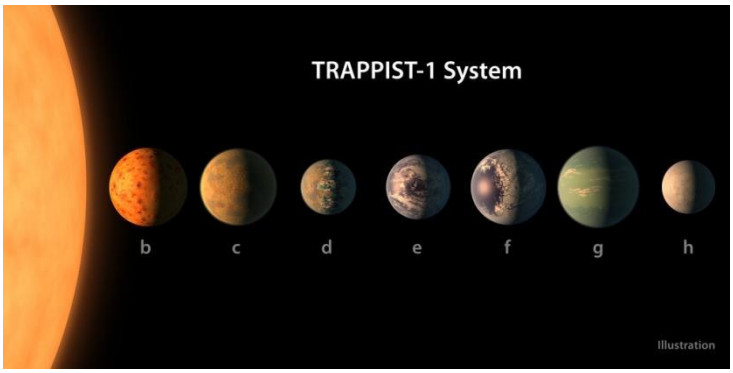
To empirically ground the theoretical tension between scientific rigor and aesthetic expression, I conducted a lightweight mixed-methods study. I investigated how different visual representational styles of exoplanet renderings influence perceptions among the general public. Three images were selected from NASA's and public archives depicting the same exoplanet TRAPPIST-1: (A) a data-rich spectral plot, (B) a standard scientific visualization adhering to known physical parameters, and (C) a highly artistic conception inspired by scientific data. Fifty participants (N = 50; 26 female, 23 male, 1 non-binary; ages 19–48, M = 31.4, SD = 7.6) were recruited via the online platform RedNote, balanced across art/science educational backgrounds (48% arts/humanities, 52% STEM). Twelve participants (6 female, 5 male, 1 non-binary) completed follow-up semi-structured interviews. All participants reported no formal training in astronomy or professional visualization.

In a within-subjects design, participants were randomly exposed to these images and asked to rate each on a 7-point Likert scale across three dimensions:

Perceived Credibility 1 = 'purely fictional' → 7 = 'scientifically accurate' ('To what extent does this image reflect the true appearance of the planet?')
Self-reported Comprehension 1 = 'did not help me understand' → 7 = 'helped me understand clearly' ('How much do you feel you understand about this planet from this image?')
Emotional Engagement 1 = 'not exciting' → 7 = 'very exciting' ('How exciting does this image make the prospect of exploring this planet?').

A final open-ended question probed the perceived appropriate context for each image (e.g., museum, textbook, news article, film). Each image was standardized to equal resolution (2200 × 1240 px), display size (15.6″ monitor), and viewing distance (~50 cm). A within-subjects, counterbalanced design was used to control for order effects. Participants viewed each image for 25 seconds, then completed a short questionnaire. Between images, a 10-second blank-screen interval minimized carry-over bias. Sessions lasted 20 minutes.Following the quantitative data collection, brief semi-structured interviews were conducted with a subset of 12 participants to elicit richer qualitative rationale behind their ratings.





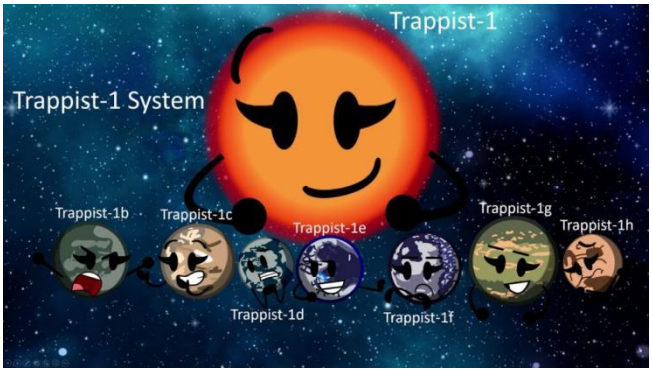


Fig 11 Three Preliminary user study images
(A) A data-rich spectral scientific plot TRAPPIST-1 Exoplanets Infrared Observations[54]
(B) Scientific visualization TRAPPIST-1 Exoplanets Lineup[55]
(C) A highly artistic conception inspired by TRAPPIST-1 planetary system[56]

Quantitative data were analyzed in SPSS 29 using repeated-measures ANOVA with Bonferroni-corrected pairwise comparisons. Qualitative interview data were transcribed and thematically coded using Reflexive Thematic Analysis (Braun & Clarke, 2019)[57]. As discussed, these images must navigate a complex space between empirical adequacy (e.g., spectroscopic data) and narrative efficacy (e.g., cultural expectations shaped by science fiction). A significant main effect of visualization style emerged for all three dimensions ($p < .001$). Image (A) scored highest on Perceived Credibility ($M = 6.2$) but lowest on engagement ($M = 2.8$). Image (C) scored highest on Emotional Engagement ($M = 6.4$) but lowest on Perceived Credibility ($M = 3.1$). Image (B) showed balanced ratings (Perceived Credibility $M = 4.8$; Emotional Engagement $M = 4.9$). Qualitative data from interviews revealed that participants often distrusted aesthetically pleasing images as ‘mere advertising' or ‘fantasy,' yet admitted that these same images sparked their curiosity and made abstract concepts feel emotionally captivating and 'humanizing.' Conversely, scientific plots were seen as truthful but cold. This directly illustrates the techno-poetic bind: maximizing one dimension (Emotional Engagement) often comes at the cost of another (Perceived Credibility). It demonstrates that this tension is not merely theoretical but is empirically measurable and central to the public's experience of cosmomedia.

This empirical glimpse into public perception underscores the high stakes involved in the design of cosmic visualizations and how representation modality directly modulates epistemic trust in scientific interfaces. The inverse correlation between perceived accuracy and emotional engagement ($r = -.64$, $p < .01$) suggests that design strategies for cosmic visualization must balance empirical transparency with aesthetic accessibility. For HCI, this points to a design space where visual realism and affective imagination function as co-variables, rather than opposites, within techno-poetic interaction design. This phenomenon undermines the purely instrumental perspective on scientific models, as the artistic depiction of data has endowed these models with an aura of 'quasi-reality'[58]. On the other hand, it also calls into question the simplistic posture of traditional realism, given that this 'quasi-reality' is fundamentally a product of technological processes. There may arise a need to foster a 'technology-mediated realism' that acknowledges scientific models as neither mere reflections of reality nor solely computational constructs, but as 'technologically constituted truths'[59] that exhibit cognitive efficacy within specific technological milieus. From this perspective, the galaxies simulated by IllustrisTNG and other simulation interface are not merely solutions to mathematical equations; they are also tangible images of the universe and manifest expressions of supercomputing infrastructure. These three elements are dialectically integrated, forming a unique paradigm for understanding the universe in the digital age.

At the confluence of science and art, a novel interaction paradigm, which may be termed 'Embodied Computational Epistemology,'[60] is emerging. This paradigm surpasses the traditional dichotomy of subject and object, dialectically unifying the abstract computation inherent in scientific modeling with the embodied perception characteristic of artistic representation. IllustrisTNG and other space simulation projects exemplify this paradigm: they are reliant on precise mathematical and physical equations, as well as on the creation of aesthetically pleasing cosmic landscapes through

visualization techniques. The cognitive aesthetic complex mediated by this technology suggests that our comprehension of the universe is fundamentally a 'computationally mediated embodied experience'. Mathematical equations are imbued with visual form, abstract concepts are rendered sensory, and cold computational data is transmuted into a dynamic narrative of the universe.

Scientific simulation's crisis of absence may also revealed, where absence catalyzes new modes of representation. If LHC (Large Hadron Collider) experiments conclusively disprove dark matter, a cornerstone of ΛCDM cosmology, the resulting epistemic vacuum would expose scientific modeling's vulnerability to constraint-based design: a scenario where the simulated (dark matter's mathematical elegance) collapses under the weight of empirical absence, leaving only the simulacrum of failed predictions. This mirrors Baudrillard(1981)'s 'precession of models', where 'the map precedes the territory,' but with a critical inversion: here, the territory negates the map. NASA's exoplanet renderings, as hybrid artifacts gain epistemic resilience precisely through their admitted fictionality. Artistic simulations thrive by foregrounding their constructedness ,e.g., labeling renderings as 'artist's interpretations'[61]. This bifurcation challenges Hacking's realism, while science risks credibility when models fail, art presupposes failure of direct representation, making it paradoxically more 'authentic' in a post-Baudrillardian sense.[62]

The LHC scenario forces a reevaluation of epistemic-aesthetic hybrid, If even high-energy physics, the paragon of quantitative modeling cannot escape hyperreal dissolution, then all scientific abstraction becomes susceptible to Baudrillard's 'murder of reality.' The 'non-detection' of dark matter, rather than invalidating scientific modeling, transforms absence into an epistemological catalyst, compelling both science and art to model through negation, e.g., cosmological simulations that now parameterize 'unknown' dark sector interactions as creative constraints, or Borgesian cartographies that map voids as constitutive features.(Trauvitch, 2024)[63] The LHC's potential falsification of dark matter doesn't merely extend the science-art hyperreality debate, it inverts it. Scientific models, when falsified, risk becoming more simulacra than art, while artistic visualizations, by embracing their artificiality, achieve a perverse epistemic honesty. This inversion demands a radical synthesis: perhaps 'authenticity' in the digital era lies not in fidelity to reality, but in the rigor of one's surrender to unreality, a surrender science may now be forced to confront. Such practices operationalize simulations as epistemic palimpsests, layering mathematical negation (e.g., exclusion plots) with aesthetic interventions to materialize the unknowable through computational poiesis.

The generation of cosmic knowledge no longer hinges on the passive reflection of 'objective reality' but is actively constructed via the embodied practice of technological perception. The interface design of SpaceX's Dragon spacecraft amalgamates engineering data, such as orbit parameters, with science fiction aesthetics reminiscent of 2001: A Space Odyssey, thereby transforming technical data into visual symbols that align with spatial cognition. This results in a cognitive loop characterized by observation operation feedback, which is the embodied cognition function of technological media. The interface design of the Dragon spacecraft not only facilitates the visualization and interpretation of engineering data but also integrates the astronaut's physical movements into the computational loop through tactile feedback and dynamic interaction, such as gesture-controlled orbit adjustments. This integration fosters a technologically augmented form of embodied cognition. UI designers serve as pivotal interface translators within this architecture of technology-mediated cognition. They convert the abstract language of aerospace engineering into co-adaptive interfaces that resonate with human perceptual patterns through multimodal interaction design. Consequently, they transform engineering data into visual symbols that are congruent with spatial cognition, thus establishing a cognitive loop of 'observation operation feedback.' The design team innovatively adapted the visual grammar of science fiction works, transforming orbital mechanics equations into dynamic visual representations and complex space navigation operations into a gestural semantics system aligned with human movement intuition. This design approach essentially constructs a techno-embodied cognitive bridge. By meticulously designing tactile feedback curves, such as vibration frequency gradients employed during docking procedures, and visual dynamic effects, including particle flow simulations of fuel consumption, the designers successfully integrated astronauts' muscle memory with the spacecraft's mathematical control system, thereby creating a novel engineering-perceptual hybrid. This groundbreaking design demonstrates that in extreme human-machine collaboration

environments, such as aerospace, UI designers have evolved from traditional aesthetic creators to cognitive architects, who redefine the ontological relationship between humans and technological systems through interfaces. This design philosophy implies that in the digital media era, the acquisition of scientific knowledge has transitioned from the conventional 'observation-modeling' paradigm to a closed-loop cognitive system of 'perception-computation-action.' In this system, technological media serve not merely as information carriers but also as an extension of cognitive capabilities. This human-machine cognitive coupling obscures the boundaries between tools and cognitive subjects, thereby rendering scientific practice itself a technologically embodied mode of existence.[64]

Figure 12 Principal UI/UX Designer working on the Crew Displays Team for SpaceX CrewDragon interface

Figure 13 UI/UX operations engineers worked directly with NASA astronauts Source: NASA/SpaceX/Shane Mielke

Baudrillard(1981)'s theory of mimesis elucidates the semiotic isomorphism that exists between scientific simulation and artistic fiction. It's worth noting that his pessimistic assertion regarding the 'disappearance of reality' does not adequately account for the productive potential inherent in digital modeling. Here, 'authenticity' shifts from correspondence to generative efficacy within networked material-semiotic practices. Through the lens of Barad(1998)'s concept of 'agential realism,' we can interpret NASA's exoplanet renderings as a practice of material symbolic entanglement. Here, spectral data and GPU rendering pipelines converge to form an apparatus of knowledge, yielding outputs that are neither entirely objective nor entirely fictional. Instead, they produce techno-mediated cosmology. [65]A visual comprehension of the distant universe is facilitated through sophisticated algorithms and advanced visual presentation techniques. This process integrates the prowess of scientific data with computational technology, giving rise to a 'hyperreality' that is both grounded in and transcends empiricism. The intricate interplay between this hyperreality and multiple ontologies exhibits significant plasticity. The identical set of raw spectral data can yield diverse forms of representation by virtue of varying algorithmic parameters and rendering methodologies. For instance, in scientific discourse, these data may serve as the foundation for constructing precise atmospheric models; conversely, in artistic exhibitions, they may be metamorphosed into immersive visual projections, affording viewers a distinctive cosmic experience. Each of these presentations constitutes a unique cognitive framework, enabling viewers to grasp the universe in varied manners across different contexts. We can discern the generative potential of digital modeling within scientific endeavors. It not only uncovers the semiotic isomorphism between scientific simulations and artistic fabrications but also elucidates the means by which a technologically facilitated cosmic ontology emerges through the entangled engagement of material and symbol.

At the algorithmic juncture where scientific simulation and artistic simulacrum converge, we are privileged to bear witness to the emergence of a cognitive infrastructure for Interaction Design. This infrastructure transcends the boundaries of being merely a scientific instrument or a cultural artifact; rather, it embodies a novel manifestation of what Stiegler terms 'tertiary retention'.[66] Through the material agency of digital media, including GPU parallel computing and latent space manipulations within neural networks, it reconfigures human imagination and comprehension of the cosmos. Within this conceptual framework, future endeavors in cosmic cognitive research may necessitate a departure from the conventional dichotomy of 'reality versus fiction', and instead embark on an exploration of the ecology of modeling practices. This

exploration entails an investigation into how diverse modeling objectives of prediction, explanation, aesthetics, and education of intermingle and metamorphose within technological networks. Only by adopting such an approach can we cultivate a cosmological perspective that is genuinely attuned to the contemporary technological milieu, one that is both meticulous and lyrical; both analytical and experiential; and ultimately, one that bridges the human and the posthuman realms.

Cosmopoetic HCI: Negotiated Materialities in Algorithmic Rituality

Yuk Hui(2022) in Art and Cosmic Technologies[67], redefining the ontological status of technological artifacts: they are not merely functional tools but also material carriers of a civilization's cosmic worldview and dismantles the myth of 'technological neutrality'. For instance, Chinese bronze ritual vessels served both as symbols of cosmic order and practical cooking utensils, with their taotie motifs directly embodying imaginations of the human-cosmos relationship. The 'Three Distances' (三远法) technique(Figure 14) in Chinese landscape painting is essentially a form of cosmic modeling technology, sharing cognitive structures with modern space telescope data visualization. The 'Three Distances' technique, a unique perspective method in ancient Chinese landscape painting, was formalized by the Northern Song painter Guo Xi (郭熙) in his treatise Lofty Messages of Forests and Streams (林泉高致).[68] Methodologically, the 'Three Distances' (high, deep, and level distance) transcend mere painting techniques, functioning as a technology to simulate cosmic spatial relationships through recursive visual frameworks, i.e., overlapping and nested perspectives. This bears striking resemblance to modern astronomy's logic of constructing cosmic models by layering multi-band data. Epistemologically, both exemplify 'technologically mediated cognition.' Song Dynasty painters achieved a dialectical unity between small-scale canvases and the vast cosmos through alternating applications of the Three Distances, while astronomers, artists and designers transform electromagnetic signals into layered cognitive affordances via algorithms for viewers to navigate cosmological scales, both reconstructing cosmic understanding through technological mediation. Thus, all civilizations engage in symbolic modeling of the cosmos through specific technological forms, whether ink brushes or CCD sensors. Hui argues that the philosophy of technology must move beyond Western-centrism, seeking new cognitive paradigms through cross-civilizational comparisons of 'cosmotechnics' to elucidate how technological media mediate rational cognition and poetic expression.

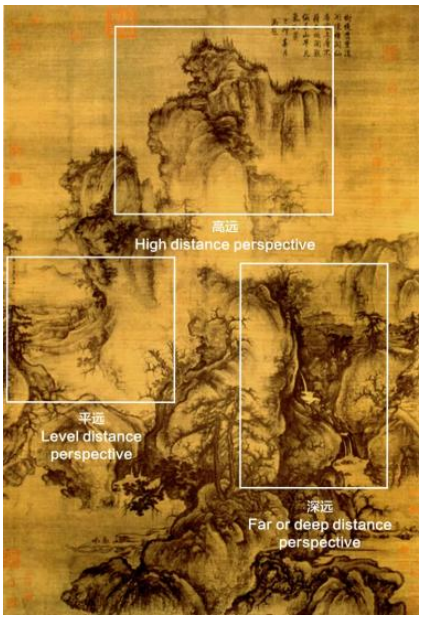


Figure 14 Guo Xi's painting 'Early Spring' is a typical example of the 'Three Distances Method' in landscape painting (the original is now in the Palace Museum in Taipei)

Figure 15 Chinese Nine Dragons Playing with a Jade Bead Inkstone Source: Beijing Arts and Crafts Museum

The ontological status of technological artifacts constitutes a privileged site for examining the entanglement of materiality

and epistemology. Consider the Chinese inkstone(Figure 15), particularly the Duan variety with its characteristic purple-cloud veining. Its significance transcends mere utility as a calligraphic tool; the stone's mineral stratification embodies Daoist cosmogony where geological time becomes legible as 'patterns of heaven' (天文, tianwen). The carving technique known as 'matching heaven with heaven' (以天合天, yi tian he tian)[69] operationalizes Zhuangzi's paradox of non-action (無為, wuwei), the artisan's chisel follows pre-existing fault lines in the stone, rendering the creative act simultaneously one of discovery. This material-semiotic complex manifests what François Jullien terms 'the propensity of things' (勢之勢,shi zhi shi),[70] where cosmological principles achieve concrete expression through skilled craftsmanship. This synthesis proposes that Confucian cosmotechnics offers an alternative to Heideggerian(1977) Gestell: in both Qing dynasty qi-based media and contemporary GPU-rendered galaxies, technology functions not as dominating interaction framing effects but as a mediating vessel (器, qi) for cosmological dao (道). The section's conclusion thus gains historical depth: the dialectic between material carriers and aesthetic construction finds precedent in China's wen (文, pattern)-based epistemology, where cosmic truths were always already techno-poetic performances.[71]

Notably, technological objects transcend conventional phenomenological frameworks through their sheer scale and intricate complexity, thereby reconfiguring the very conditions of human perception and embodied cognition. Juxtaposed with this ancient artifact, the gold-plated beryllium mirrors of the James Webb Space Telescope (JWST) present a contemporary hyperobject in Timothy Morton(2023)'s sense[72], each mirror segment performs triple interaction modality taxonomies: as a interaction uncertainty models device capturing infrared photons, as a cultural prosthesis extending human vision beyond evolutionary limits, and as a material metaphor for what Don Ihde calls 'technologized gaze.'[73] The mirror's 18 hexagonal segments deliberately echo the honeycomb structure, unconsciously replicating nature's optimal packing solution while pursuing optical perfection, a convergence of biomimetic principle and engineering rationality that parallels the inkstone's geological aesthetic.[74] This comparative analysis reveals what might be termed the hermeneutic density of technological objects. Their material configurations simultaneously encode mathematical-physical causality, and phenomenological intentionality, the inkstone's tactile feedback guiding brushwork. The superposition of these regimes constitutes what contemporary philosophy of technology recognizes as 'technological a priori' the preconditioning of human experience through artifact-mediated reality. Gilbert Simondon, in On the Mode of Existence of Technical Objects (1958), introduces the idea of technology's 'pre-individual dimension,' positing that technical systems possess an autonomous evolutionary logic prior to human engagement, which is a perspective that implicitly advances a theory of technological transcendence. Technological a priori operates as a latent structuring principle, where the material-semiotic affordances of artifacts preconfigure perceptual horizons and cognitive schemata prior to conscious reflection. It manifests as an irreducible conditionality, human experience is always already mediated through historically sedimented technical forms that transcend individual intentionality while enabling meaningful engagement with the world. Don Ihde, in Technology and Praxis (1979)[75] and Technology and the Lifeworld (1990)[76], He draws his inspiration from Hidegger's 'tool analysis' proposes the 'theory of technological mediation,' which asserts that technologies are not neutral instruments but rather 'hermeneutic mediators' that reconfigure human perception and modes of being. This conceptual framework furnishes the phenomenological groundwork for the notion of 'technological a priori.'[77]

Techno-phenomenology with sensor arrays generates synthetic noemata through algorithmic processing as techno-cognitive hybridity. This epistemological rupture becomes particularly evident when examining the operational paradigm of NASA's Perseverance rover in Jezero Crater[78]. The robotic arm's sample-collecting maneuvers exist in synchronous ontological registers such as, physical processes strictly governed by Hamiltonian mechanics and constrained by Martian gravitational parameters ($g=3.72076\ m/s^2$); As hermeneutic gestures that materialize planetary scientists' narrative frameworks about Martian aqueous history through the very angle of drill penetration (typically 50-55° to optimize sample integrity). As cultural performances that generate what I term 'interplanetary haptics', the collective psychological phenomenon where terrestrial observers experience proprioceptive echoes of the robotic appendage's movements.[79] The profound implication lies in how this technological engagement collapses the observer/observed distinction. When the rover's abrasion tool exposes Martian stratigraphy, it doesn't simply reveal pre-existing geological truths but co-constitutes them through the very parameters of its intervention much like how the uncertainty principle dictates that measurement conditions fundamentally

alter quantum systems.[80] This constitutes nothing less than an ontological paradigm shift, where cosmic technology becomes the literal embodiment of the universe comprehending itself through recursive material-semiotic loops.[81]

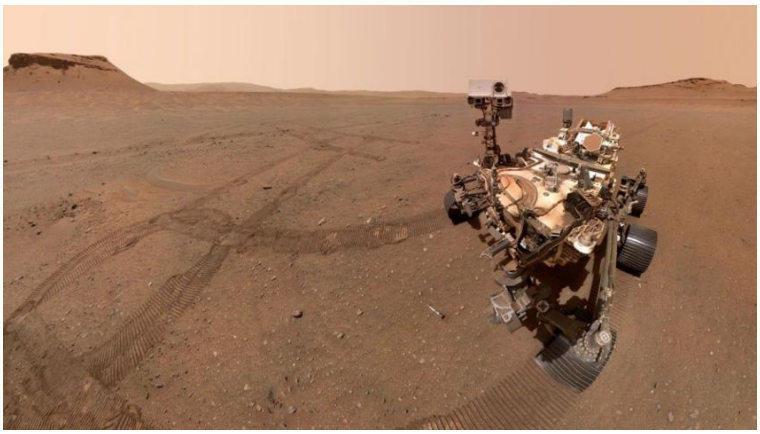


Figure 16 Perseverance's Three Forks Sample Depot Selfie. NASA's Perseverance Mars rover
Source: NASA/JPL-Caltech/MSSS
Figure 17 William Anders, Earthrise, 1968 Source: NASA

The techno-poetic dimension of space exploration manifests most vividly through the praxis of data-image transmutation. Consider the iconic 'Earthrise' photograph captured by Apollo 8(Figure 17)[82], while its raw scientific data comprised merely high-contrast grayscale pixels, its eventual manifestation as the luminous blue marble floating in cosmic darkness constitutes what we may term perceptual optimization a process requiring careful unpacking. This transformation operates through what philosopher Benjamin Lazier conceptualizes as the 'inscription of meaning' paradigm, wherein scientific objects, such as photon signals registered by CCD sensors must undergo rigorous techno-poetic operations before emerging as culturally legible symbols. The complexity lies in the dual-aspect nature of these operations: color mapping procedures employ standardized chromatic scales not as passive translation keys, but as active epistemological frameworks that co-constitute planetary visibility. When NASA technicians selected specific RGB values to represent atmospheric scattering effects in the Earthrise image[83], they weren't merely reconstructing physical reality but performing what Husserl would call 'intentional acts of consciousness' the blue hue simultaneously obeys radiative transfer equations while evoking terrestrial fragility. This constitutes cognitive-aesthetic double modeling at its most potent, algorithmic parameters (white balance adjustments, gamma corrections) serve as latent philosophical propositions about how cosmic phenomena should be apprehended.[84]

Contemporary Mars rover imaging systems exemplify this legacy through high-dynamic-range synthesis techniques. The Perseverance's panoramic mosaics don't document the Martian surface; they construct perceptual interfaces where mineralogical data (iron oxide concentrations) merges with human Perceptual color mapping (CIE LAB color space calibrations). Such technical choices embody what Don Ihde describes as 'technological hermeneutics' every JPEG compression ratio decision implicitly prioritizes certain modes of cross-scalar cognition over others. The fundamental revelation here transcends space photography: all scientific visualization is ultimately techno-poetic praxis, where epistemic rigor and Designerly intentionality perform an intricate pas de deux across the gradient fields of raw data and shared interaction semantics. This analytical framework necessitates transcending the instrumentalist paradigm of traditional philosophy of technology, embracing instead what Yuk Hui conceptualizes as cosmotechnics, an epistemological shift that reconceptualizes technological artifacts as interfaces mediating between Tangible interaction protocolss and cosmological imaginations. The ontological turn in cosmotechnics fundamentally challenges Heidegger(1977)'s critique of technology as Gestell (interaction framing effects), proposing instead that technologies function as embodied interaction layers that co-constitute our being-in-the-universe. When Apollo 8's 'Earthrise' photograph transformed planetary perception through its pixel matrix, or when exoplanetary atmospheric simulations render the invisible visible, we witness techno-poetic practices that reconfigure human embodied cognition at cosmic scales and generate cosmological meanings through iterative design loopses. These are not merely instrumental operations, but embodied interaction metaphors.

Hongfeng Tang(2024)'s 'Ren(Benevolence), Virtual Image and Common Sense: Cosmomedia and Political Philosophy in Modern China'[85] offers a poetic recalibration of HCI through its triad of ren (benevolence), virtual imagery, and common sense. addressing the 'crisis of representation' in modern cosmology requires embracing what Tang (2024) identifies as a 'mediated moral cosmology,' recognizing that interactive tools from magic lanterns to real-time N-body simulations are never neutral mediators. Instead, they function as constitutive elements within an ongoing cosmotechnical poiesis, deeply intertwined with human interpretation and intervention. What fascinates me is how this framework reimagines interfaces as cosmopoetic rituals, where algorithmic processes don't just compute, but mediate between cosmic energies (氣 qi) and human political consciousness. The theory's insistence on disappearing distance as a site of ethical negotiation challenges our transactional view of interaction design, proposing instead a model where digital materialities emerge through negotiated attunements. Avoiding both positivist literalism and postmodern hyperrealism and provides a robust foundation for designing ethically aware, participatory astrophysical visualization systems that align technical practices with deeper human and cosmic values. If interfaces can embody weiqi's ether-like fluidity, then user-system interactions become performative acts of cosmic harmony. The common sense cultivated in such systems isn't merely functional, it's a shared sensibility that bridges Confucian ren with contemporary algorithmic governance. It's clear that cosmopoetic HCI isn't just about designing for planetary challenges but designing as planetary challenges, where every interaction carries the weight of negotiating materialities across metaphysical and political scales.

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