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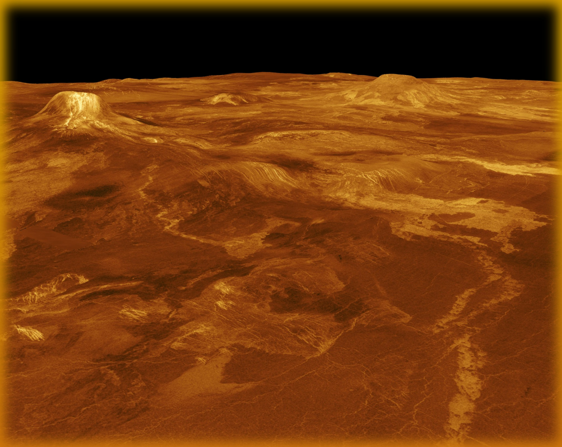
a journal on cutting edge astrophysics
research, tools, and people

SCIENCE ASCEND



INTERVIEWS

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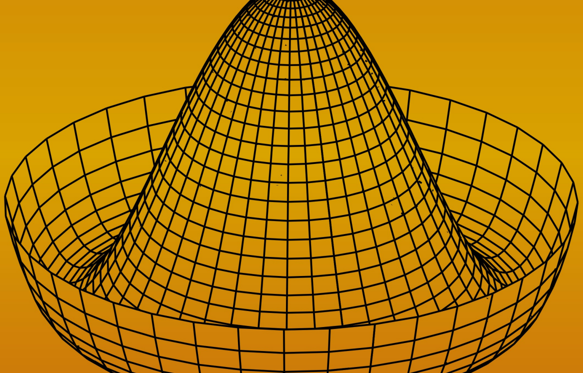

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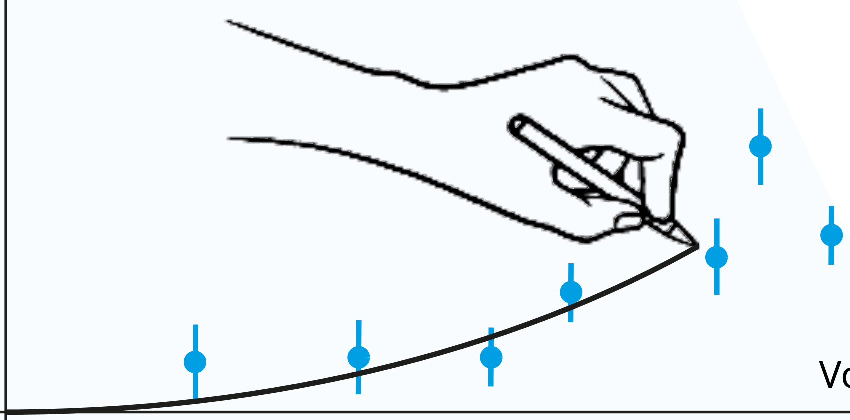

SCIENCE ASCEND

Vol. 3, Issue 2, July 2026

PREFACE

Greetings everyone!

Lots of new things happened in the preceding 6 months!

Science Ascend focused more on interviews, lecture notes, and expert opinions. Thanks to more frequent advertisements, we were able to publish it with four interviews and four articles by experts/academicians.

Akos Kereszturi wrote to illustrate the impact of planetary comparisons in teaching geological surfaces. Arif Solmaz prepared an article on reproducibility in astrophysics research. Maarten Roos-Serote continued his Venus opinion articles with a quite curious Venus Express piece. Last but not least, Özlem Yeşiltaş continued with the cosmic strings lectures with a theoretical introduction to their fundamental concepts.

Furthermore, all published articles starting from the previous issue are archived in Zenodo and indexed in OpenAIRE.

See you in the next issue!

Güray Hatipoğlu
FIRE Research and Training Ltd.

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TECHNICAL INFORMATION

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Interview with Erika Pakštienė

Erika Pakštienė is a full-time faculty member in the Institute of Theoretical Physics and Astronomy at Vilnius University. She graduated from Vilnius Pedagogical University (now Vytautas Magnus University) Department of Physics & Chemistry, followed by a master's in the same university's Physics and Astronomy department. After these, she pursued a Ph.D. at Vilnius University's Institute of Theoretical Physics and Astronomy with the title "Extinction of the Earth's atmosphere in multicolour photometry". Throughout this period, she worked as a physics teacher in a secondary school, an engineer, and a researcher.

Her main research field is asteroseismology – the study of stellar interiors through their pulsations. She began her scientific career investigating pulsating white dwarfs and, in recent years, has focused on stars with solar-like oscillations, using them to determine stellar ages and evolutionary stages and to improve our understanding of the evolution of the Milky Way Galaxy.

She has participated in numerous international observing campaigns, including the Whole Earth Telescope (WET) network. Her scientific interests also include eclipsing binary stars and exoplanets. She was the first researcher in Lithuania to initiate observations of exoplanet transits.

Besides her research, she has been active in education and science outreach, too. She has served as an evaluator at the International Physics Olympiad, developed astronomy assignments for the distance-learning physics school FOTONAS, contributed to the development of two STEAM educational activity methodologies for the STEAM Centre in Vilnius, co-authored educational materials for physics teachers, contributed astronomy chapters to educational publications, and authored numerous popular science articles on astronomy.
She was also among the 5 Lithuanian scientists nominated for the 'Honour of Lithuania' award for her involvement in the exoplanet discovery by microlensing (AT2021uey, link*).*
The asteroid 270903 Pakstiene (2002 TO303, link *) discovered by Kazimieras Černis was named in her honour in 2021.*

Q1- You have extensive experience with telescope observations, teaching how to utilize it, and processing its signal. What are your:
a. The most memorable experience during your observation campaigns,

It is difficult for me to identify a single most memorable observing experience. There have been many of them, because I started my first scientific observations almost thirty years ago.

Many of my first experiences in observational astronomy remain among my strongest memories. One of them was my first observing run with the 165 cm telescope at the Molėtai Astronomical Observatory, when I felt both pride and responsibility as I operated such a large scientific instrument for the first time. .

Similar feelings accompanied my first observing campaigns at the Teide and La Palma observatories in the Canary Islands, where I had the opportunity to work in an international environment, meet colleagues from different countries, and observe the sky from some of the best observatories in the world.

Another memorable aspect of observing campaigns was the strong sense of cooperation in observatories around the world. In the years before long-term space-based photometry became available, continuous observations were possible only through international collaborations. Many observers, often separated by thousands of kilometres, worked together as one team, each contributing a small part to a much greater scientific effort. This shared purpose made such campaigns especially rewarding.

However, sometimes the most memorable moments are not the observations themselves but unexpected natural phenomena. One such event happened in 2023 at the Molėtai Observatory. While preparing for remote observations, I noticed unusually bright patches in the sky on the observatory webcams. At first, I did not understand what I was seeing. After reviewing a time-lapse video, I realized that they were very bright aurorae. Such events are relatively rare in Lithuania, and on that occasion the aurora was visible across almost the entire sky. It was one of the most impressive natural phenomena I have ever observed at Molėtai Observatory.

I also clearly remember my surprise during a night observing run at the Teide Observatory when my car became covered with ice while the air temperature was still +8°C. As a physicist, I can explain the process, but even for a physicist, it was quite unexpected.

b. The one that taught you the most

In reality, the greatest lessons are learned not when everything goes smoothly, but when you face unexpected situations: new instruments, new observing techniques, technical failures, or unfavorable weather conditions.

Over the years, I have learned that successful observations depend not only on astronomical knowledge but also on discipline and careful work. One of the most important lessons I have learned, and one that I always pass on to beginning observers, is the importance of having a clear checklist.

This is especially important at the end of an observing run, when observers are often tired, and it becomes easy to forget an important step. For example, someone may forget to stop telescope tracking or overlook another procedure required for the safe shutdown of the system. Such mistakes may put expensive observatory equipment at risk and can create unnecessary problems for the next observing session.

Perhaps the most important lesson I learned is that successful observations depend as much on practical experience and attention to detail as on scientific knowledge. Many problems cannot be solved by theory alone and require quick decisions based on experience gained at the telescope.

2- How was your experience working on the “Whole Earth Telescope” network studies?

The Whole Earth Telescope (WET) network was my gateway into asteroseismology.

Although my PhD research was related to atmospheric extinction, during a summer school organized by our institute, Prof. Jan-Erik Solheim from the University of Tromsø in Norway suggested applying the atmospheric extinction correction method I had developed to WET observations. That became my first step toward asteroseismology.

In 2002, I participated in the WET conference in Naples, Italy, where I presented my method. I became fascinated by variable stars, the diversity of their pulsations, and the possibility of studying stellar interiors through asteroseismology. This field later became one of my main scientific interests.

I participated in WET campaigns in several different roles. I carried out observations both at the Molėtai Astronomical Observatory and with the Nordic Optical Telescope on La Palma. I also had the opportunity to work at the WET headquarters in Ames, Iowa, USA, where I became familiar with the coordination of an international observing campaign, real-time data processing, and the organization of a global observatory network.

Later, I also organized two WET observing campaigns dedicated to the DAV white dwarf PG 2303+243. I subsequently performed the asteroseismic analysis of the data collected by multiple observatories worldwide. This allowed me to experience WET not only as an observer and campaign participant, but also as a campaign organizer and principal investigator.

This experience showed me how observatories around the world can operate as a single instrument in order to achieve continuous observations. Although today we receive a large amount of high-quality data from space missions such as TESS, international observing campaigns remain important. The main difference is how they are organized has changed. Today, coordination, communication, and data exchange are mostly done remotely, allowing researchers from different countries to collaborate efficiently.

3- You worked on many different types of astronomical objects. What are the hurdles, remarks, your favourite among them, and especially if there was a challenge after changing the type of astronomical object to study?

Yes, during my career, I have observed many different types of astronomical objects, including pulsating white dwarfs, eclipsing binary stars, exoplanet transits, artificial Earth satellites, rotating asteroids, and others. Some of these observations were related to my own research, while others were part of projects led by other researchers. I always find it exciting to start working with a new type of object because each raises different scientific questions and requires understanding different physical processes.

If I had to choose a favourite group of objects, it would be objects with variable brightness. When an object does not vary, a single observation is often enough. When it varies, every new observation can provide additional information. Whether it is a pulsating white dwarf, an eclipsing binary, or an exoplanet transit, changes in brightness over time contain valuable information about the physical properties and internal structure of these objects. For this reason, light-curve analysis has always been one of my favourite areas of astronomical research.

If I had to mention one specific object, I would choose an eclipsing binary discovered at the Molėtai Astronomical Observatory in 2019. It is a particularly complex system. The stellar orbits are eccentric; the stars experience tidal distortions when they approach each other, and one of the components is a pulsating Delta Scuti star. As the stars periodically approach each other, their gravitational interaction distorts their shapes, and we observe changes in the system's brightness.

Such systems are not easy to study, but they can provide very accurate results because we obtain additional information both from the orbital geometry of the eclipsing binary and from asteroseismology. We are still studying this system.

The biggest challenges usually come not from the type of object itself but from observing conditions and technical limitations. For example, when observing geostationary satellites or space debris, the calculated position is often not accurate enough. If the field of view of a telescope is too small, the object has to be searched for in neighbouring sky fields around its predicted location. Such observations sometimes resemble a game of hide-and-seek.

Another constant challenge is the weather. Even carefully planned observations can fail if clouds arrive at the most important moment. Astronomers cannot control the weather or the behaviour of the objects they observe. Astronomical objects do not follow a work schedule. Eclipses, transits, and other short-lived events occur whenever nature decides they should occur, regardless of weather, weekends, or holidays. We sometimes say that astronomers do not work according to a schedule; they work according to the sky. As a result, this profession teaches patience, flexibility, and the ability to adapt. It is also common for astronomers to end their messages with the traditional wish: “Clear skies.”

4- You have papers with single to several, to multiple, to many authors, and you joined collaborations with different numbers of people. What are your remarks on working in different group sizes?

During my career, I have worked both independently and in small, medium-sized, and very large international research groups. Each type of collaboration has its own advantages and disadvantages.

Working alone provides more freedom to make decisions and choose the direction of the research. However, it also means you have to do everything yourself, from observations and data analysis to interpreting the results and preparing the paper. This often makes the research process considerably slower. In addition, there are fewer opportunities for regular discussions and feedback from colleagues.

In my opinion, small and medium-sized groups, with roughly 5 to 15 active researchers, are often the most efficient. In such groups, every member can make a significant contribution to the final result. Research decisions are discussed within the team, and results are usually obtained and published more quickly.

At the same time, large international projects are also very important. In astronomy, it is often necessary to organize long-term observing campaigns involving many observatories and researchers from different countries. In such cases, a long author list usually reflects not simply formal participation, but the need to combine the efforts of many people to collect the required data. Without this type of collaboration, many studies would simply not be possible.

Therefore, I believe that the most important factors are not the size of the group, but clearly defined goals, good communication, and a clear understanding of each person's role within the project. Although large international collaborations are often unavoidable in astronomy, I personally feel most comfortable working in a smaller research group.

5- How can we make science popularization/outreach activities successful?

Although I consider myself primarily a researcher rather than a science communicator, I believe that the public should have the opportunity to learn what scientists do and why their work is important.

Over the years, I have participated in various educational activities and have seen that people are usually most interested when they can get a glimpse of real scientific work. In my opinion, successful science outreach should show why science matters and how it is connected to everyday life. Audiences are often more interested in stories, discoveries, and the process of scientific research than in technical details.

Direct involvement is also very important. Opportunities to ask questions, participate in observations, experiments, or other hands-on activities help people stay interested for longer. When someone becomes part of the process, science becomes more meaningful and easier to understand.

At the Molėtai Astronomical Observatory, we organized summer schools dedicated to astronomy outreach. Students worked in small groups and prepared short videos on different astronomy topics. It was interesting to see how differently people could present the same scientific information. Groups found its own way of engaging the audience, and the final results were often surprisingly creative.

This experience showed once again that successful science outreach requires not only knowledge but also creativity. In addition, the best results are often achieved when several people work together and combine different ideas and perspectives.

Today, social media and digital platforms also play a very important role in science outreach because they allow us to reach much larger audiences than traditional events alone.

6- What is your current research interest that intrigues you?

There are many areas of astronomy that interest me. However, throughout most of my career, asteroseismology has remained the field that fascinates me the most.

Asteroseismology provides a unique opportunity to study the internal structure of stars through their pulsations, because information about stellar interiors cannot be obtained through direct observations.

What I particularly enjoy is that every variable star is like a puzzle. As we analyse its pulsations, our understanding of the star gradually develops, piece by piece, much like solving a jigsaw puzzle. Although modern methods are becoming increasingly automated, the analysis of many variable stars still requires a scientist's experience, intuition, and creativity.

I am also very much looking forward to the European Space Agency's PLATO mission. It will provide an enormous amount of high-quality photometric data and open new opportunities not only for asteroseismology but also for studies of exoplanets and other variable objects.

More generally, what I find most exciting about astronomy is that there re still so many unanswered questions. The more we learn, the more new questions appear

7- Do you have any suggestion for astrophysics graduate students?

One of the most important pieces of advice I would give to students today is to learn how to use artificial intelligencewisely.

AI has become an easily accessible tool that can help with learning, generating ideas, searching for information, understanding difficult concepts, and even suggesting new research directions.

However, it is very important to maintain critical thinking. AI should not replace a student's ability to analyse information, evaluate sources, or solve problems independently. It should be used as a tool and assistant, not as a substitute for your own thinking or as a friend who does your homework for you.

My second piece of advice would be to find a topic that genuinely interests you. Scientific research requires a great deal of time, patience, and persistence, so motivation becomes extremely important. If you have a clear goal and are truly interested in what you are doing, it becomes much easier to overcome difficulties.

Interview with Maarten Roos-Serote

This interview features a dialogue between Güray Hatipoğlu (founder of FIRE Research and Training Ltd. and Science Ascend journal) and Maarten Roos-Serote (astrophysicist, software developer, and documentary filmmaker at Light-Curve Films). The discussion centres on the critical need for digital sovereignty, data privacy, and European-hosted alternatives to mainstream, US-dominated software and services.

1. The Imperative for Digital Sovereignty

The speakers note a shifting cultural mindset toward data tracking, user profiling, and geopolitical vulnerabilities. A major driver for seeking European alternatives is the US Cloud Act (2018), which permits the US government to mandate access to corporate data under security pretexts, creating operational risks for international entities using mainstream US software.

2. Online Meeting & Collaboration Platforms

Mainstream tools like Zoom have achieved monopoly status, but secure, localized options are expanding:

- Hostpoint Meet: A Swiss-hosted, Jitsi-based open-source platform. It features unlimited one-to-one meeting times, requires no registration, and delivers high-performance recordings optimized for video editing due to its tight three-second keyframe architecture.
- Whereby: A Norwegian platform ideal for recurring team meetings and webinars. It offers permanent room links and scalable paid tiers, allowing up to 100 participants across multiple rooms.

3. Web Browsing & Network Privacy

To mitigate automated user tracking and profiling, the speakers highlight tools offering structural privacy:

- Vivaldi Browser: Developed in Norway by an Opera co-founder, it features advanced native productivity tools, including highly organized "Workspaces" for tab management, without tracking user data.
- Proton VPN & Ecosystem: Created by former CERN particle physicists and based in Switzerland, Proton provides a zero-log security architecture. The free tier offers rapid connectivity to select international nodes, facilitating secure browsing and helping bypass regional content restrictions.

4. Search Infrastructure

The discussion contrasts the current state of dominant search technology with independent indices:

- Mainstream Issues: Modern mainstream search engines have increasingly shifted toward ad-heavy results and forced AI summaries, diminishing their efficiency compared to historical indexing methods.
- Qwant: A privacy-focused French search engine building its own independent index. It avoids user tracking and profiling, delivering direct results without AI-generated summaries.

5. Instant Messaging Apps

Here, the main theme was data collection and security risks while instant messaging.

- Whatsapp: Subject to the US CLOUD Act, hence, high risk of automated profiling. Signal is a much ethical choice, though it is also US-based with a similar risk.

- Delta Chat: Europea-based alternative with a decentralized architecture through e-mail networks. However, it does not support audio and/or video calls natively.
- Threema: Swiss-based application with a fully secure encryption and privacy. It is not free, but only for a one-time nominal price.

6. Document Production & Real-Time Collaboration

The transition away from dominant corporate document suites requires tools that preserve formatting fidelity while maintaining encrypted workflows:

- CryptPad: A French-hosted, zero-knowledge collaborative suite. It utilizes OnlyOffice in the backend, supporting spreadsheets, documents, and real-time project tracking. The speakers noted high stability (over 99% operational success) with only rare, network-related interruptions.
- Murena Workspace: A rapidly emerging French cloud ecosystem. It provides fully integrated email, cloud file sharing, and document editing, with commercial enterprise versions and upcoming native online meeting tools currently in active development.

7. Mobile Operating Systems

Digital sovereignty on desktop environments is frequently limited by upfront hardware investment costs; however, major strides have been made in the mobile sector:

- The /e/OS Ecosystem: A fully "de-Googled," privacy-hardened open-source Android operating system championed by Murena. It eliminates background location telemetry and user tracking while remaining fully compatible with mainstream mobile hardware.
- Application Sideloading: Rather than relying on the Google Play Store, users can seamlessly utilize independent, open-source app repositories (such as F-Droid) to install community-driven utility applications.

8. Office Software UI & Formatting Interoperability

When migrating away from Microsoft Office, users face clear structural trade-offs between two major open-source suites:

- LibreOffice

Development & Longevity: A legacy branch of OpenOffice/Apache OpenOffice with a continuous open-source update cycle.
UI Adaptability: Features a unique interface layout; cell/table dimensions in document modules can require dedicated configuration menus.
Interoperability Limitations: Complex layouts and modern XML-based templates (.docx) can occasionally experience alignment and layout shifts when parsed.

- OnlyOffice

Development & Longevity: Specifically architected to mirror contemporary office suite ergonomics.
UI Adaptability: Highly intuitive interface that directly clones standard Microsoft layouts, minimizing user learning curves.
Interoperability Limitations: Exceptional rendering accuracy when opening and editing native corporate formats, reducing layout degradation during grant proposals.

9. Software Repositories

The speakers evaluated repository sovereignty for research software development, highlighting a critical academic bottleneck:

- Codeberg: A non-profit, privacy-focused Git hosting platform based entirely in Germany. It provides a clean, web-based repository interface, active community bug reporting, and zero AI-training telemetry on codebase contents. Despite Codeberg's functional parity with Microsoft-owned GitHub, mainstream scientific journals exclusively accept or look for GitHub links for software publications, presenting a major systemic barrier to full open-source migration.

10. Design, Layout, & Spatial Mapping

For publishing layouts and spatial science, open-source graphic suites have achieved full professional parity:

- Inkscape: A robust, open-source vector graphics editor replacing Adobe Illustrator and CorelDRAW. It allows for direct ingestion of native Illustrator files and is used to design the layouts for *Science Ascend*. It completely replaces basic LaTeX PDF generation with dynamic visual control.
- QGIS: A highly stable geographic information system (GIS) utilizing modern Python 3. It has been adopted by the Europlanet Society for lunar, Venusian, and Martian geological surface mapping, successfully breaking the vendor lock historically imposed by commercial platforms like ArcGIS.

11. Professional vs. Analytic Video Editing Pipelines

Video post-production demands vary heavily depending on project complexity, leading to two distinct alternative pathways:

- DaVinci Resolve (Blackmagic Design)

Architecture: A comprehensive, professional-grade suite that evolved from dedicated color-grading software into an industry-standard editor.

Licensing Model: Rejects regular subscription fees in favor of a sustainable, one-time lifetime license fee.

Platform Support: Represents the only flagship, professional non-linear video editing suite natively optimized to run smoothly on Linux/Unix systems.

- FFmpeg (Command-Line Processing)

Architecture: A lightweight, highly efficient command-line tool ideal for low-end hardware configurations or server-side workflows.

Performance: Drastically reduces rendering overhead by performing direct stream copies. It executes simple cuts or trims along keyframes (e.g., Hostpoint's 3-second keyframe limits) in fractions of a second, completely bypassing long Adobe Premiere render queues.

Analytical Control: Demystifies video containers by allowing users to treat files analytically—enabling separate manipulation of metadata, audio tracks, and subtitles without needing to re-render the underlying video stream.

The Culinary Analogy: The speakers liken standard video suites to ordering a ready-made meal at a restaurant—convenient, but rigid. Using FFmpeg is akin to understanding the exact raw ingredients of a recipe; it demands more baseline technical knowledge, but allows the user to optimize, substitute, and control the final product with total analytical precision.

12. Conclusion & Outlook for Emerging Researchers

The interview concluded with an emphasis on mutual, community-driven learning as the primary mechanism for breaking tech monopolies. As digital landscapes shift rapidly due to geopolitical forces and changing corporate data policies, the speakers offered a final piece of guidance directed at astrophysics graduates and the broader scientific community:

- Community Knowledge Exchange: Navigating the ecosystem of open-source and sovereign European alternatives is an iterative, collective process. Broad adoption relies entirely on users testing them, reporting bugs, and sharing their workflows.
- Maintaining Research Aspiration: In a fast-changing technological landscape where data tracking is ubiquitous, maintaining digital sovereignty is intrinsically tied to academic and professional freedom. The fundamental advice to the next generation of researchers is to resist systemic inertia, actively seek out open-source tools, and remain driven by internal scientific aspirations rather than commercial software ecosystems.

The interview can be watched link

Interview with Mark Wieczorek

We interviewed Mark Wieczorek, one of the key figures in planetary science and open science. Here are his answers to the interview's questions below:

1- Introducing yourself briefly

I am originally from the United States. I studied geophysics at Washington University in St. Louis, completed a postdoctoral position with Maria Zuber at Massachusetts Institute of Technology (MIT), and later moved to France, where I joined CNRS in 2003.

Scientifically, I consider myself a planetary geophysicist. My research focuses on planetary gravity fields, topography, magnetic fields, impact cratering, and planetary interiors. Much of my work relies on spacecraft data. I have been involved in major missions such as GRAIL, which mapped the Moon's gravity field and InSight, Psyche, as well as the ongoing missions BepiColombo, JUICE and Psyche.

2- The first time you considered using/creating alternatives to USA and/or big corporation services, your reasons.

Outside planetary science, I became increasingly dissatisfied with the direction in which large technology companies are headed. Over roughly a decade, I watched software become more commercialized, more invasive, and often less useful. Indeed, companies collected enormous amounts of personal data while adding features users never requested. This gradually pushed me toward open-source alternatives.

For me, open-source software offers several advantages. It respects privacy, gives users control over their own data, and allows bugs or problems to be addressed transparently. Even if I cannot fix a problem myself, I can report it and often see the issue resolved. I see this as fundamentally different from the closed ecosystems of large corporations.

I emphasize that moving away from proprietary platforms is a gradual process. Nobody should expect to replace everything overnight. The practical approach is to replace one tool at a time—for example, moving from Gmail to a privacy-focused email provider, or from Microsoft Word to LibreOffice. Over time, these changes accumulate. Furthermore, after making sure the app/service transition took place, it is quite comfortable to change even the operating system to Linux from Windows or MacOS.

3- Your (and your communities') experiences with

a. Twitter vs. Mastodon

Regarding social media, I strongly believe researchers should leave X (formerly Twitter). I see it as increasingly dominated by polarization and low-quality discourse. I regard both Mastodon and Bluesky as viable alternatives, but I prefer Mastodon.

My preference for Mastodon comes from several factors. It is fully open source, operates within the broader Fediverse ecosystem, provides a less hostile environment, encourages more thoughtful discussion, and avoids algorithmic content manipulation. While it currently has fewer users than Bluesky, I find the quality of interaction substantially better.

b. slack vs. mattermost

For team communication, I advocate replacing Slack with Mattermost. My interest in Mattermost grew after Slack restricted access to message history and increasingly pushed commercial features. Mattermost provides essentially the same functionality while remaining under user control. I also expect platforms like Discord to eventually face the same commercial pressures that affected Slack. Worse still, I am particularly critical of Microsoft Teams. In my experience, it is cumbersome, slow, and often adopted because institutions purchase large Microsoft bundles rather than because it is the best technical solution.

c. *Peertube*

One project I am especially proud of is PeerTube. I see it as a genuine alternative to YouTube. Through our planetary-science-focused server, SolarSystem.video, we provide a curated collection of scientific talks and educational material. Unlike YouTube, where scientific content is often buried beneath sensationalized, AI-generated, or conspiratorial material, our platform is designed specifically to help people find serious planetary science content efficiently without unrequested advertisements.

d. *Signatories*

In my view, researchers frequently need an open signatory service to gather support for:

- mission proposals,
- white papers,
- community letters,
- petitions,
- letters of support.

Existing solutions are usually commercial, track users, hard to check the authenticity, or are not designed for academic communities. Signatories was created as an open-source alternative that allows scientific communities to organize and sign public statements while retaining control of the platform and data. The broader idea is that infrastructure for scientific governance should belong to scientists themselves, not to private companies. Researchers sign petitions both anonymously or directly with their unique ORCID so that everyone can be sure the signatories are real people.

e. Liberaforms

Similarly for Signatories, Scientists constantly need:

- conference registrations,
- surveys,
- committee elections,
- community questionnaires,
- proposal submissions.

Instead of proprietary services such as Google Forms or Microsoft Forms, the Cooperative hosts its own LiberaForms server. The emphasis is on privacy, data ownership, open-source software, and community control. It is even more powerful than Google Forms with more, beneficial features ensuring end-to-end encryption, ownership transfer, and much better usability.

f. Indico

Scientific communities need much more than journals. We organize workshops, conferences, seminar series, and community meetings all the time. Most people simply use whatever commercial platform is available, but I wanted infrastructure that the community actually controls.

That's why we adopted Indico. It is mature, open-source conference-management software already used by many research institutions. Through SolarSystem.events, we can manage registrations, abstracts, schedules, and meetings without depending on commercial providers. For me, this is part of a larger philosophy: scientific communication infrastructure should belong to scientists.

4- Summary on how the Planetary Research journal and Planetary Research Cooperation were founded.

Planetary Research is probably the project that best represents what I think scientific publishing should become. I became increasingly frustrated with a system where publicly funded research is often locked behind paywalls, while authors are also asked to pay large publication charges. The economics simply do not make sense to me.

With Planetary Research, we wanted to build a genuine diamond open-access journal. Readers pay nothing. Authors pay nothing. The journal is run by the community rather than by a commercial publisher. At the same time, I do not believe open access should mean lower standards. The goal is to maintain rigorous peer review and high editorial quality while removing unnecessary financial barriers.

More broadly, I see the journal as an experiment in whether a scientific community can reclaim ownership of scholarly publishing and operate it for the benefit of researchers rather than shareholders. The Cooperative emerged because I gradually realized that publishing is only one piece of the problem. Scientists communicate, collaborate, organize meetings, share videos, discuss results, recruit collaborators, and publish papers. Most of those activities are currently dependent on large corporations.

My view is that scientists should own the infrastructure that supports science. The Cooperative is an attempt to build that infrastructure. The journal, the Mastodon server, PeerTube, Mattermost, Indico, LiberaForms, Signatories, blogs, and other services are not separate projects in my mind. They are parts of a single ecosystem.

I am not arguing that everyone must abandon commercial platforms tomorrow. What I am arguing is that scientific communities should have independent alternatives that they govern themselves.

If we can communicate, organize, publish, and collaborate on infrastructure that is open, transparent, and community-owned, then science becomes more resilient and less dependent on decisions made by companies whose priorities may not align with the interests of researchers.

Ultimately, the Cooperative is my attempt to demonstrate that a different model is possible: one where the scientific community builds and maintains its own digital commons.

5- Is there anything you would like to say to the astrophysics/planetary scientists and candidates?

As I have already mentioned in this interview, please use the tools we develop! They are free, no money will be charged, and in case permission or an account is required, such as with our Indico or mattermost servers, it usually doesn’t take more than 5 minutes of our time to set up.

The interview can be watched link

IInterview with Wolfgang E. Kerzendorf

We had an interview with Prof. Wolfgang E. Kerzendorf in 22 January 2026, starting with a brief introduction to his professional career and elaborating on its several milestones.
Through his academic career, Wolfgang Kerzendorf obtained his Vordiplom[1] in Physics from the Universität Heidelberg. This is followed by a summer research work at Mount Stromlo Observatory, and then, a Ph.D. in the same place with the following title: Type Ia supernovae: Progenitors and explosions, obtained in 2011 link .

His story continued (and still continues) with ever more successes. He held a Postdoctoral Researcher position in the University of Toronto, and then, he was an ESO Fellow at the European Southern Observatory between 2014 and 2018. He also worked at NYU and Flatiron Institute until the middle of 2019.
Now, he is an Assistant Professor in the Michigan State University, Department of Physics & Astronomy and Computational Mathematics, Statistics, & Engineering.

Elaborating on his Ph.D., it was on Type Ia supernovae. His early research during a PhD at Mount Stromlo Observatory focused on identifying possible companion stars, though later results showed such companions are rare or absent in expected forms. His PhD and early career were strongly shaped by hands-on observational astronomy, mentoring, and large collaborations. He emphasized that PhD training is less about demonstrating intelligence and more about sustained motivation and curiosity-driven work, often requiring intense focus over long periods. The interview has critical remarks on this, such as ‘quitting is underrated’, to emphasize that one can hope to successfully finish a Ph.D. and make a dissertation worth reading when s/he is also passionate about the subject.

After the PhD, his trajectory was highly non-linear and shaped by chance interactions. Key steps included postdoctoral work in Toronto, involvement with the Astropy Project, and later positions in Europe and the US. He highlights the importance of collaboration fit, open-source culture, and interdisciplinary environments as decisive career factors.

A major methodological contribution from his group is “emulation” approaches that dramatically accelerate expensive simulations (including neural-network-based surrogates), enabling faster astrophysical inference. One example was their work with the radiative transfer code TARDIS, which they accelerated by a factor of 100 million. He also emphasizes early adoption of machine learning in astrophysics, before it became mainstream.

Beyond astrophysics, he developed a parallel research direction in computational meta-science. This focuses on the “science of science”: tracking scientific output at scale, uniquely identifying researchers, mapping expertise, and improving peer review and collaboration systems. He argues that modern science has outgrown traditional structures due to exponential growth in publications and researchers.

His group explores algorithmic matching of expertise and improved infrastructure for scientific communication, with an emphasis on open-source tools rather than proprietary systems. The curious part is that an important milestone for this was a casual dinner meeting and him saying it as just another thing he was interested in other than his scientific portfolio. His counterpart stated the significance of this and expected it in his scientific portfolio rather than a hobby, which was among the things that his interdisciplinary view welcomed.

He also stresses a methodological caution: modern large language models are useful but not universally optimal for expert matching or scientific structuring tasks, and simpler or older statistical methods can sometimes outperform them.

On astrophysical transients, his current work focuses on connecting high-fidelity simulations with observations of explosive events such as supernovae and neutron star mergers. A key example is interpreting events like GW170817, which link gravitational waves, kilonova emission, and heavy element production (including gold and uranium). His group investigates how such events produce elements and how often they occur.

Overall, his message is that modern scientific careers are nonlinear, shaped by interdisciplinary exposure and chance opportunities, and that impactful research increasingly lies at the intersection of physics, computation, and large-scale data systems rather than within single traditional disciplines. Furthermore, the necessary drive comes from inner motivation and passion, and we need to be open-minded and crazy enough (not too much to miss the payments) to seize opportunities.
The interview can be watched link

Venus Express 20 Years: Volcanoes and Sulphur

On 11 April 2006, the first European spacecraft arrived at Venus to stay. Approved only three years before its launch, late 2005, Venus Express is the fastest mission ever managed by the European Space Agency to date. I recall serving on the Solar System Working Group in 2002. This is one of the four advisory bodies for ESA's Science Programme with rotating members from the relevant science communities. We were presented with a mission opportunity to use spare elements from the Rosetta mission (launched in 2004) and the Mars Express mission (launched in mid-2003). Rosetta was a cornerstone mission in ESA's Science Programme, developed from scratch. Mars Express was a spin-off of Rosetta, and hence Venus Express can be considered a grandchild of Rosetta. Of these three missions, Mars Express is still orbiting Mars and collecting useful scientific data. The fast development track for Venus Express was, of course, thanks to the reuse of the existing spare spacecraft bus and spare instruments.

The decision by the ESA member states to use the Rosetta and Mars Express spares to go to Venus was taken in 2002, the contract with industry was formally signed in early 2003 (Fabrega et al. 2003), and the launch occurred in late 2005. The mission formally ended in December 2014, and the spacecraft was sent into the atmosphere of Venus to disintegrate.

The mission cost on the industry side was under 100 Meuros, less than 10% of the cost of the Rosetta mission, and I think it is fair to state that the science-per-Euro-ratio for Venus Express must be one of the best of all missions of the agency to date.

ESA's task is to take care of providing the spacecraft, through European industry, getting it to its destination, and operating it. The payload, however, the instruments, are made by dedicated teams of scientists and engineers from European institutes, and are paid for separately by ESA member states. Just one of the seven instruments on Venus Express, the Venus Monitoring Camera, was newly developed. The other six were inherited from Mars Express (ASPERA, PFS, and SPICAV) and Rosetta (VIRTIS, VeRa, and MAG).

Venus Express marked a return to Venus! The last dedicated mission to Venus had been Magellan (NASA), which mapped the surface of Venus for the first time using radar, and studied the gravity field, between late 1990 and late 1994. It carried no other instruments.

Between Magellan and Venus Express, two spacecraft used Venus' gravity to gain speed on their way elsewhere: Galileo to Jupiter in February 1990, Cassini/Huygens to Saturn in April 1998 and June 1999. On these occasions, useful data, but limited amounts, were collected.

In fact, the Galileo Near Infrared Mapping Spectrometer data provided with the confirmation of theoretical calculations presented a few years earlier, that pointed at the existence in the near infrared of a narrow window, at 1.18 micron, through which the surface can be observed, albeit not very 'sharp' due to atmospheric interference: like seeing the bottom of a lake through a column of moving water (Kamp et al. 1988, Carlson et al. 1993). Ever since Galileo confirmed this possibility, any spacecraft going to Venus has been carrying the capability to observe this wavelength range.

The VIRTIS instrument and the VMC camera on Venus Express both covered this wavelength region. One of the results that caused excitement was the observation that surface emissivity values derived from VIRTIS data in regions related to volcanic structures are very high compared to the rest of the surface. This could be indicative of recent volcanic activity (Smrekar et al. 2010). More recently, reanalysis of Magellan radar data showed changes at the surface in a two-year time span, which could be related to current lava flows (Sulcanese et al. 2024) and the existence of lava tubes (Carrer et al. 2026).

Venus Express collected data about the sulphur dioxide (SO2) concentrations at the cloud levels during its active years. Before Venus Express, data collected by the Pioneer Venus mission (NASA) between 1978 and 1992 revealed that the abundance of SO2 decreased significantly over that time period. The mystery of the variation of SO2 at the cloud levels deepened as data from Venus Express added to the long timeline: it showed a steep rise at the beginning of the mission, followed by a similar decline as seen with Pioneer Venus over several years (Marcq et al. 2012). Whether or not this is connected to episodes of volcanic activity remains unclear at this point, but the possibility exists. Long-run ground-based observations (2012 – now) performed and presented by Encrenaz et al. (2025 and references therein) point to the existence of strong variation at short and long temporal and spatial scales from regional to global.

After Venus Express, the Japanese Akatsuki mission collected a large data set between 2015 and 2024, when contact was lost. Today, there is no spacecraft orbiting Venus. A new mission is being developed at this moment at ESA called Envision. It will become active in the mid 2030s. With a powerful suite of instruments, Envision will be observing Venus from the interior all the way to the upper atmosphere. The collected data will also be used to address the SO2-mystery, and more discoveries are to be expected! In the meantime, we have to continue to observe Venus from Earth and from the rich space-based data sets that exist and that most certainly contain several hidden treasures to be uncovered.

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References

Carlson, R. W., Baines, K. H., Girard, M., Kamp, L. W., Drossart, P., Encrenaz, T., & Taylor, F. W. (1993). Galileo/NIMS near infrared thermal imagery of the surface of Venus. Lunar and Planetary Science Conference Proceedings, 24, 253–254. https://articles.adsabs.harvard.edu/pdf/1993LPI....24..253C

Carrer, L., Diana, E., & Bruzzone, L. (2026). Radar-based observation of a lava tube on Venus. Nature Communications, 17, Article 1147. https://doi.org/10.1038/s41467-026-68643-6

Encrenaz, T., Greathouse, T. K., Giles, R., Widemann, T., Bézard, B., Lefèvre, F., Lefèvre, M., Marcq, E., Sagawa, H., & Shao, W. (2025). HDO and SO_2 thermal mapping on Venus: VII. SO_2 variations with altitude and influence of the solar cycle. Astronomy & Astrophysics, 703, A219. https://doi.org/10.1051/0004-6361/202556250

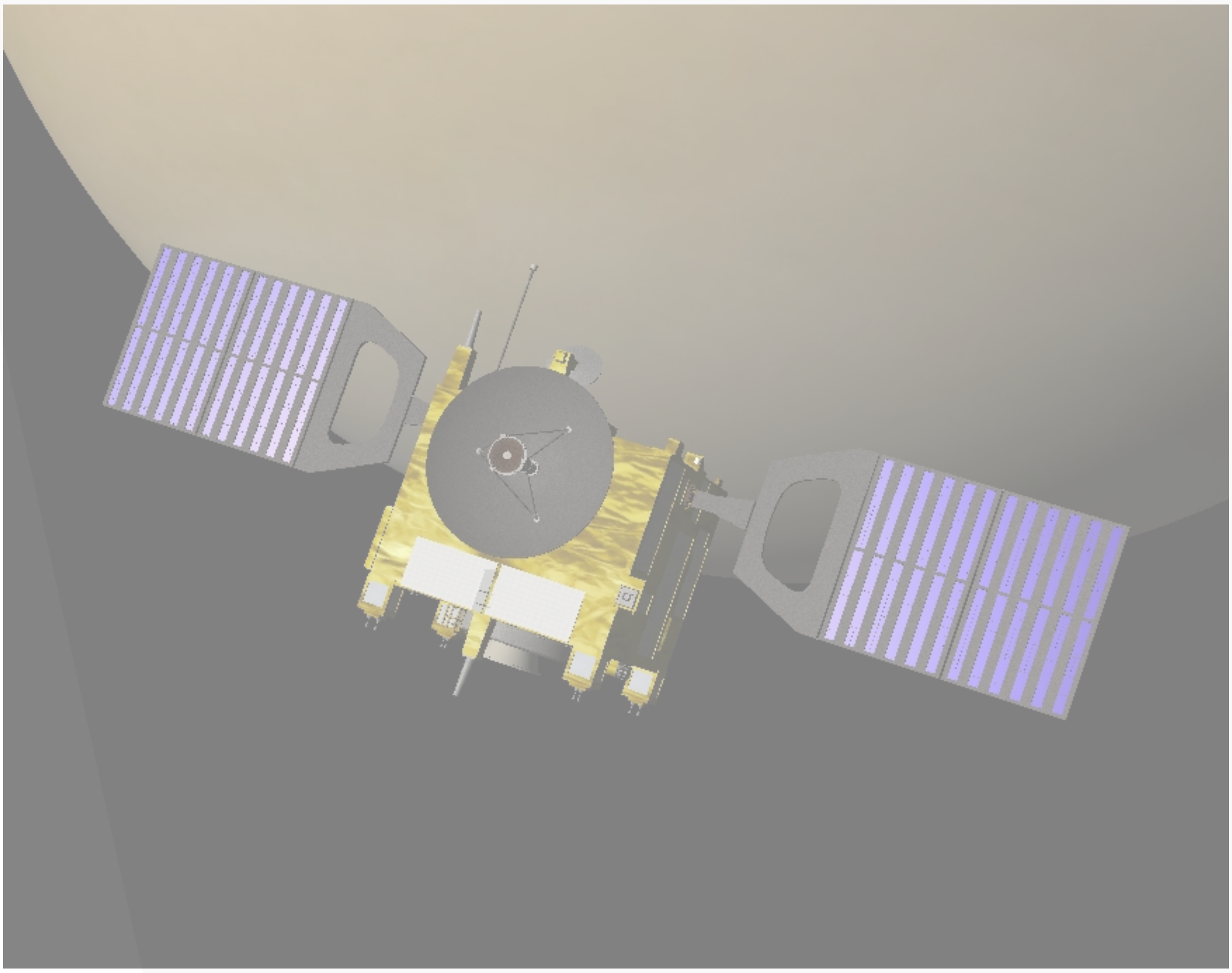
Fabrega, J., Schirmann, T., Schmidt, R., & McCoy, D. (2003). Venus Express: First European mission to Venus. In Proceedings of the 54th International Astronautical Congress (Paper IAC-03-Q.2.06, pp. 1–11). EADS Astrium. https://sci.esa.int/web/venus-express/-/34843-venus-express-first-european-mission-to-venus

Kamp, L. W., Taylor, F. W., & Calcutt, S. B. (1988). Structure of Venus' atmosphere from modelling the night-side infrared spectra. Nature, 336, 360–362. . https://doi.org/10.1038/336360a0

Marcq, E., Bertaux, J.-L., Montmessin, F., & Belyaev, D. (2013). Variations of sulphur dioxide at the cloud top of Venus's dynamic atmosphere. Nature Geoscience, 6(1), 25–28. https://doi.org/10.1038/ngeo1650

Smrekar, S. E., Stofan, E. R., Mueller, N., Treiman, A., Elkins-Tanton, L., Helbert, J., Piccioni, G., & Drossart, P. (2010). Recent hotspot volcanism on Venus from VIRTIS emissivity data. Science, 328(5978), 605–608. https://doi.org/10.1126/science.1186785

Sulcanese, D., Mitri, G., & Mastrogiuseppe, M. (2024). Evidence of ongoing volcanic activity on Venus revealed by Magellan radar. Nature Astronomy, 8, 973–982. https://doi.org/10.1038/s41550-024-02272-1



Venus Express

When Astronomy Cannot Be Reproduced

When we imagine modern astronomy, we usually think of massive telescopes on mountaintops, advanced space detectors, and the beautiful cosmic images sent down by observatories such as the James Webb Space Telescope. But if we look closely at how modern astrophysics actually works, one of its most important instruments is not made of glass or mirrors. It is made of code.

Today, much of cosmic discovery depends on digital workflows. Data archives, Python scripts, digital notebooks, version-control systems, and online repositories have become part of the scientific method. A published astronomical image is rarely a simple camera snapshot; it is usually the result of calibration, filtering, modeling, and visualization choices.

This creates a serious vulnerability. When these digital layers are hidden in private folders, left undocumented, or tied to temporary commercial software licenses, the scientific result is difficult to inspect. Even a famous, peer-reviewed finding can be a black box: visible as a conclusion, but difficult for other scientists to repeat, test, or preserve.

Open-source tools are therefore much more than cheap alternatives to commercial software. They are part of the infrastructure that keeps science reliable. Examples from modern astrophysics, including the BICEP2 cosmic-dust controversy and the Event Horizon Telescope's image of the black hole in M87, show that reproducibility is not an abstract academic ideal. It is a practical requirement for strong, trustworthy science.

The Hidden Instruments of Modern Astronomy

Astronomy has always depended on tools. Historically, the telescope was the defining instrument of discovery. But in 2026, the telescope is often only the first stop in a long scientific chain. A modern astronomical discovery may depend just as heavily on database queries, calibration pipelines, software libraries, plotting scripts, and cloud storage platforms.

These digital tools are our hidden instruments. They rarely appear in press releases or headlines, but they transform raw signals from space into a scientific claim that can be examined by other researchers.

Consider what happens before a discovery is published. A final chart in an article is not a direct snapshot of nature. It is the product of many steps:

- Raw data is downloaded from a digital archive.
- Bad pixels, instrumental effects, or atmospheric noise are filtered out.
- Physical units are converted, and data-quality flags are applied.
- A mathematical model is selected, a fitting algorithm is executed, and a visual plot is generated.

If this digital chain is visible and documented, other researchers can inspect it, learn from it, and trust it. But if the steps are hidden inside private folders, closed-source software, or undocumented manual edits, the science becomes harder to verify. Even when the raw data is public, the final result may be nearly impossible to reproduce.

The core issue is not that commercial or private software is inherently bad. Many proprietary tools are powerful and have served science well for decades.

The real question is simpler: can the vital path from raw data to a published conclusion be inspected, taught, and preserved for the next generation? Open-source workflows matter because they make that path more transparent.

Reproducibility is a Workflow Problem

In computational astronomy, people sometimes mistake reproducibility for simply sharing data. But sharing a raw dataset is no longer enough. A dataset becomes scientific evidence only after it passes through a specific workflow.

Without a clear record of the software versions, quality filters, model assumptions, and visualization decisions used, a final table or graph is incomplete. It is like an equation with half the numbers missing.

This is where software dependence becomes an epistemic problem: it affects our ability to know what is true. A data workflow might run perfectly in a well-funded university today. But what happens when a graduate student leaves the team, a software license expires, a local operating system updates, or a commercial software company changes its pricing model? The analysis may become unrecoverable.

Astrophysics research can suffer from three forms of systematic lock-in:

- License lock-in: scientific training and data analysis become restricted to institutions that can afford temporary software contracts.
- Format lock-in: observational data is saved in closed or poorly documented file types that future tools may not read easily.
- Knowledge lock-in: analysis steps exist only in the mind of one researcher, leaving little institutional memory when that person moves on.

Open-source tools do not magically solve all of these problems. Badly written code can still confuse collaborators, and a public GitHub repository without a clear README is not automatically reproducible. However, open-source tools make testing, migration, teaching, and preservation more realistic. They help the scientific community move from blind trust in a software box toward direct inspection of the research process.

Real Lessons from Published Astronomy

The need for open and reproducible workflows is not only a philosophical debate. The history of published astronomy already contains important examples where hidden assumptions, independent data, or open validation changed the status of a major claim.

One of the best-known examples is the BICEP2 case. In 2014, the BICEP2 collaboration announced evidence for B-mode polarization in the cosmic microwave background, the ancient light left over from the Big Bang. The result attracted global attention because it was interpreted as possible evidence for primordial gravitational waves from cosmic inflation.

However, the interpretation depended heavily on how polarized dust emission from the Milky Way was modeled. Later, a joint analysis combining BICEP2/Keck data with observations from the European Space Agency’s Planck satellite found strong evidence for Galactic dust contamination and no.

statistically significant evidence for primordial tensor modes. In other words, the original inflationary interpretation was no longer robust once the foreground dust was accounted for.

The lesson is not that the BICEP2 team was careless. The lesson is that high-level astronomical interpretation depends on external data, independent checks, and transparent workflows. The observation was real, but the cosmological interpretation required a pipeline that other scientists could test against additional data.

A more positive example is the Event Horizon Telescope (EHT), which produced the first image of a black hole shadow in the galaxy M87. This result achieved wide trust partly because the collaboration did not depend on only one software pipeline or one group of programmers.

For the 2019 M87 imaging analysis, the EHT collaboration used a two-stage procedure. First, four imaging teams worked independently and blindly, using both the established CLEAN method and regularized maximum-likelihood methods. Then the collaboration tested imaging parameters against synthetic data, comparing reconstructions with known ground-truth images. Across these tests, the ring diameter and asymmetry remained stable.

Later reproducibility work extended this openness by creating an open-source, containerized software package that allowed the public to reproduce the first image of M87 from available EHT artifacts. In this case, transparency did not weaken the discovery. It made the result easier to trust, teach, and revisit.

A Systematic Problem

These are not isolated. Studies suggest astronomy faces a persistent problem with hidden or fragile workflows.

Lior Shamir and collaborators examined research-source-code availability in astronomy and astrophysics and found that many authors did not make their code publicly available. In one ASCL-related effort, only about 13 percent of contacted authors agreed to share code publicly. This makes independent replication harder than it needs to be.

A later study by Alice Allen, Peter Teuben, and P. Wesley Ryan examined source-code availability and link persistence in astrophysics articles. Their study identified hundreds of software instances and thousands of hyperlinks, showing that software is deeply embedded in modern astrophysics but is not always archived in stable, reusable ways. Link persistence also matters: if the web address to code or data disappears, the scientific trail becomes weaker.

These cases show that open-source astronomy is not simply about saving money on software licenses. It is about protecting the integrity of the scientific path. Sometimes openness protects a strong discovery from unfair doubt. Sometimes it shows that a result needs revision. In both cases, science wins.

Open-Source Astronomy is Professional Infrastructure

The old idea that open-source software is merely a cheap substitute for commercial programs is outdated. Today, open-source tools form part of the professional infrastructure of global astronomical research.

The scientific Python ecosystem gives researchers a shared language. NumPy supports numerical computation; Matplotlib supports scientific visualization; and Jupyter Notebooks allow scientists to combine code, computational results, equations, and explanatory text in one document. These tools are not hobbyist extras. They are part of everyday scientific practice.

The power of open-source astronomy is especially visible in several mature projects:

- Astropy provides community-developed Python tools for astronomy, including support for FITS files, tables, coordinates, units, time systems, constants, and related infrastructure.
- SunPy supports open solar-physics analysis and provides tools for working with solar data.
- MESA, Modules for Experiments in Stellar Astrophysics, is an open-source stellar-evolution code used for modeling how stars change over time.
- TOPCAT gives astronomers an interactive way to inspect, filter, plot, and manipulate large astronomical tables and source catalogs.

The true strength of modern astronomy does not lie in any single package. It lies in the connection between them.

A student can inspect a catalog in TOPCAT, write a Python script using Astropy to analyze targets, document the logic in a Jupyter Notebook, and track each modification with Git. Because these tools communicate through open standards and widely used formats, they create a more resilient chain of discovery.

What Students and Researchers Gain

For students, open-source astronomy provides something essential: a more level playing field. A beginner with an ordinary laptop can access public archives, run public notebooks, and use the same widely available libraries as researchers at wealthy institutions. This does not make research easy, but it lowers the financial barriers to participation.

Open tools also teach the scientific method more directly. When a student works with code, handles file formats, manages version history, and learns to fix errors, they see how a scientific result is built. They learn that science is not only a final graph or a conclusion. It is a series of traceable decisions.

The benefits extend across an academic career:

- For early-career researchers, open tools create portable expertise. Skills in Python, Astropy, Jupyter, and Git belong to the researcher, not to an institution’s license server. These skills remain useful across universities and also transfer into data science, engineering and scientific communication.
- For research groups, open workflows make collaboration easier to inspect. An advisor can check the code behind a figure. Collaborators can rerun an analysis after a sample changes. When a graduate student leaves, the next student can continue from a documented pipeline instead of rebuilding the project from memory.
- For institutions, open practices build resilience. A department that trains students only inside closed software ecosystems creates fragile expertise. If funding changes or platform policies shift, the workflow may break. Teaching open formats and archived workflows helps preserve institutional knowledge.

A Practical Open Workflow: From Archive to Figure

A reproducible astronomy project does not need to be overwhelming. Even a small undergraduate project can model strong scientific habits.

Imagine a student project that downloads public star-catalog data and builds a color-magnitude diagram. To make the final chart transparent and reliable, the student can follow a simple workflow:

1. Data Access Record the exact archive name, the data release version, the specific search query, and the date the data was accessed.
2. Visual Inspection Use open tools like TOPCAT to look at the columns, check the units, and find obvious errors or outlier points before writing code.
3. Scripted Analysis Move all data processing steps into clean Python scripts or Jupyter Notebooks so the entire calculation can be rerun with a single click.
4. Figure Generation Program the final publication charts directly from the code. Never make manual, unrecorded edits using a graphic design program.
5. Version Control Use Git to track every code modification, linking every new version of a chart to a specific state of the project.
6. Permanent Preservation When the work is ready, upload the code, the processed data, and clear run instructions into a stable, public repository like Zenodo.

This workflow does not guarantee that the science will be free from mistakes. Instead, it makes mistakes easier to find and correct.

If a final plot looks wrong, the group can trace the code line by line. If a referee asks how a star sample was filtered, the answer is recorded in the script. If a student graduates, the project remains organized and ready for the next researcher.

As a project grows from a thesis to a major international survey, the same logic scales upward. A beginner may need only one notebook and a short README file. An advanced project may require environment files, automated tests, formal software releases, and archived data products. At every level, the principle remains the same: the path from raw space data to scientific claim should leave a traceable record.

Beyond Software: Platforms and Preservation

Open-source practice is broader than replacing one commercial application with a free alternative. Modern scientific work also depends on cloud platforms: code-hosting sites, shared drives, browser-based text editors, project-management tools, and digital communication channels. These tools make collaboration easier, but they also introduce new forms of technical dependence.

Researchers may host code on a commercial server, write papers in a browser-based editor, store data in the cloud, and discuss in a team chat. None of this is inherently wrong. The problem appears when the final scientific record has no secure exit route.

Accounts can be deactivated, terms of service can change, storage limits can shrink, and personal websites can disappear.

Many readers have encountered older papers where links to original data or software no longer work. A workflow that relies entirely on one private account or one commercial platform is fragile.

Researchers therefore need to distinguish active collaboration from long-term preservation:

- During a project, teams can use convenient tools for daily work.
- At publication, supporting materials should become durable. Code should be released in a versioned form, important outputs should be moved to independent archives, and metadata should be clear.
- A shared cloud folder is not a permanent archive. A team chat thread is not scientific documentation.

This is why the FAIR principles matter. Digital research objects should be findable, accessible, interoperable, and reusable. In daily research, this means recording data sources, using open and documented file formats, archiving stable software releases, and making the pipeline understandable to an outside scientist.

A Compact Checklist for Resilient Astronomy Workflows

A workflow does not need to be perfect to be valuable. The following checklist is a practical minimum standard for student theses, small collaborations, and standard research papers.

-Can the data source be identified? Always record the exact archive name, release version, search query, and access date.

-Can the analysis be rerun? Keep clean scripts or notebooks that directly generate your main figures and tables.

-Can the environment be reconstructed? List your exact package versions or provide a standard text file (requirements.txt or environment.yml).

-Can code changes be traced? Use Git to track edits and connect specific chart versions to specific code states.

-Can a new reader understand the project? Include a short, clear README file detailing your folder structure and run instructions.

-Can output be regenerated? Ensure every published figure is explicitly linked to the code that created it.

-Are your file formats open? Prefer well-documented, universally accessible formats like FITS, VOTable, CSV/ECSV, Markdown, and LaTeX.

-Can the work survive the project? Archive your reusable code, processed data, and notebooks in a stable repository like Zenodo.

-Are tools and data properly credited? Formally cite the software libraries, digital surveys, and data archives you used.

-Is there a clear exit route? Keep independent, exportable backups of your work so you never depend on a single commercial platform.

This checklist is not paperwork for its own sake. It is a shield against common causes of scientific loss: undocumented data steps, hidden dependencies, manual plotting edits, and disappearing web platforms.

Conclusion: Open Tools as Scientific Resilience

Open-source alternatives in astronomy are no longer secondary choices or experimental hobbies. They are part of the infrastructure required for responsible modern science.

.They help ensure that knowledge of the universe remains inspectable and usable after local software licenses expire, commercial platforms change, or research institutions shift their budgets.

The goal is not ideological purity. Modern astrophysics will continue to use mixed workflows, including mission-specific pipelines, specialized commercial software, and community-developed packages. The practical question at the end of every project is simpler: can the essential parts of this work be inspected, documented, transferred, and preserved?

If tyes, the science is stronger.

For students, open tools offer broader access to astronomical research and portable technical skills. For researchers, they make results easier to verify and build upon. For institutions, they reduce lock-in and preserve institutional memory. As astronomy owns larger telescopes and does deeper surveys, the field's future will be shaped not only by what we observe, but also by how openly and durably we turn raw data into understanding.

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Bibliography

Ade, P. A. R., Aghanim, N., Ahmed, Z., Aikin, R. W., Alexander, K. D., Arnaud, M., Aumont, J., Baccigalupi, C., Banday, A. J., Barkats, D., Barreiro, R. B., Bartlett, J. G., Bartolo, N., Battaner, E., Benabed, K., Benoît, A., Benoit-Lévy, A., Benton, S. J., Bernard, J.-P., … (BICEP2/Keck and Planck Collaborations). (2015). Joint Analysis of BICEP2/ Keck Array and Planck Data. Physical Review Letters, 114(10), 101301. https://doi.org/10.1103/PhysRevLett.114.101301

Ade, P. A. R., Aikin, R. W., Barkats, D., Benton, S. J., Bischoff, C. A., Bock, J. J., Brevik, J. A., Buder, I., Bullock, E., Dowell, C. D., Duband, L., Filippini, J. P., Fliescher, S., Golwala, S. R., Halpern, M., Hasselfield, M., Hildebrandt, S. R., Hilton, G. C., Hristov, V. V., … (BICEP2 Collaboration). (2014). Detection of B -Mode Polarization at Degree Angular Scales by BICEP2. Physical Review Letters, 112(24), 241101. https://doi.org/10.1103/PhysRevLett.112.241101

Allen, A., Teuben, P. J., & Ryan, P. W. (2018). Schroedinger's Code: A Preliminary Study on Research Source Code Availability and Link Persistence in Astrophysics. The Astrophysical Journal Supplement Series, 236(1), 10. https://doi.org/10.3847/1538-4365/aab764

Committee on Reproducibility and Replicability in Science, Board on Behavioral, Cognitive, and Sensory Sciences, Committee on National Statistics, Division of Behavioral and Social Sciences and Education, Nuclear and Radiation Studies Board, Division on Earth and Life Studies, Board on Mathematical Sciences and Analytics, Committee on Applied and Theoretical Statistics, Division on Engineering and Physical Sciences, Board on Research Data and Information, Committee on Science, Engineering, Medicine, and Public Policy, Policy and Global Affairs, & National Academies of Sciences, Engineering, and Medicine. (2019). Reproducibility and Replicability in Science (p. 25303). National Academies Press. https://doi.org/10.17226/25303

Harris, C. R., Millman, K. J., Van Der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Van Kerkwijk, M. H., Brett, M., Haldane, A., Del Río, J. F., Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. Nature, 585(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Hunter, J. D. (2007). Matplotlib: A 2D Graphics Environment. Computing in Science & Engineering, 9(3), 90–95. https://doi.org/10.1109/MCSE.2007.55

Kluyver Thomas, Ragan-Kelley Benjamin, Pérez Fernando, Granger Brian, Bussonnier Matthias, Frederic Jonathan, Kelley Kyle, Hamrick Jessica, Grout Jason, Corlay Sylvain, Ivanov Paul, Avila Damián, Abdalla Safia, Willing Carol, & Jupyter Development Team. (2016). Jupyter Notebooks – a publishing format for reproducible computational workflows. In Positioning and Power in Academic Publishing: Players, Agents and Agendas. IOS Press. https://doi.org/10.3233/978-1-61499-649-1-87

Nigro, C., Deil, C., Zanin, R., Hassan, T., King, J., Ruiz, J. E., Saha, L., Terrier, R., Brügge, K., Nöthe, M., Bird, R., Lin, T. T. Y., Aleksić, J., Boisson, C., Contreras, J. L., Donath, A., Jouvin, L., Kelley-Hoskins, N., Khelifi, B., … Sinha, A. (2019). Towards open and reproducible multi-instrument analysis in gamma-ray astronomy. Astronomy & Astrophysics, 625, A10. https://doi.org/10.1051/0004-6361/201834938

Patel, R., Roachell, B., Caíno-Lores, S., Ketron, R., Leonard, J., Tan, N., Vahi, K., Brown, D. A., Deelman, E., & Taufer, M. (2022). Reproducibility of the first image of a black hole in the galaxy m87 from the event horizon telescope collaboration. Computing in Science & Engineering, 24(5), 42–52. https://doi.org/10.1109/MCSE.2023.3241105

Paxton, B., Bildsten, L., Dotter, A., Herwig, F., Lesaffre, P., & Timmes, F. (2011). MODULES FOR EXPERIMENTS IN STELLAR ASTROPHYSICS (MESA). The Astrophysical Journal Supplement Series, 192(1), 3. https://doi.org/10.1088/0067-0049/192/1/3

Shamir, L., Wallin, J. F., Allen, A., Berriman, B., Teuben, P., Nemiroff, R. J., Mink, J., Hanisch, R. J., & DuPrie, K. (2013). Practices in source code sharing in astrophysics. Astronomy and Computing, 1, 54–58. https://doi.org/10.1016/j.ascom.2013.04.001

Taylor, M. (2017). TOPCAT: Desktop Exploration of Tabular Data for Astronomy and Beyond. Informatics, 4(3), 18. https://doi.org/10.3390/informatics4030018

The Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., Earl, N., Starkman, N., Bradley, L., Shupe, D. L., Patil, A. A., Corrales, L., Brasseur, C. E., Nöthe, M., Donath, A., Tollerud, E., Morris, B. M., Ginsburg, A., Vaher, E., Weaver, B. A., Tocknell, J., Jamieson, W., … Astropy Project Contributors. (2022). The Astropy Project: Sustaining and Growing a Community-oriented Open-source Project and the Latest Major Release (v5.0) of the Core Package*. The Astrophysical Journal, 935(2), 167. https://doi.org/10.3847/1538-4357/ac7c74

The Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray, E., Aldcroft, T., Davis, M., Ginsburg, A., Price-Whelan, A. M., Kerzendorf, W. E., Conley, A., Crighton, N., Barbary, K., Muna, D., Ferguson, H., Grollier, F., Parikh, M. M., Nair, P. H., … Streicher, O. (2013). Astropy: A community Python package for astronomy. Astronomy & Astrophysics, 558, A33. https://doi.org/10.1051/0004-6361/201322068

The Event Horizon Telescope Collaboration, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Baczko, A.-K., Ball, D., Baloković, M., Barrett, J., Bintley, D., Blackburn, L., Boland, W., Bouman, K. L., Bower, G. C., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., … Yamaguchi, P. (2019). First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole. The Astrophysical Journal Letters, 875(1), L4. https://doi.org/10.3847/2041-8213/ab0e85

The SunPy Community, Barnes, W. T., Bobra, M. G., Christe, S. D., Freij, N., Hayes, L. A., Ireland, J., Mumford, S., Perez-Suarez, D., Ryan, D. F., Shih, A. Y., (Primary Paper Contributors), Chanda, P., Glogowski, K., Hewett, R., Hughitt, V. K., Hill, A., Hiware, K., Inglis, A., … (Sunpy Contributors). (2020). The SunPy Project: Open Source Development and Status of the Version 1.0 Core Package. The Astrophysical Journal, 890(1), 68. https://doi.org/10.3847/1538-4357/ab4f7a

Wilkinson, M. D., Dumontier, M., Aalbersberg, Ij. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., Da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., … Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data, 3(1), 160018. https://doi.org/10.1038/sdata.2016.18

Wilson, G., Bryan, J., Cranston, K., Kitzes, J., Nederbragt, L., & Teal, T. K. (2017). Good enough practices in scientific computing. PLOS Computational Biology, 13(6), e1005510. https://doi.org/10.1371/journal.pcbi.1005510

Zenodo. (2026). About zenodo. CERN Open Science Platform. Retrieved in July 2, 2026 from: https://about.zenodo.org/

Environmental comparison in the planetary science education in Hungary

Abstract

Comparative evaluation of landforms for Earth and space science university was to widen their knowledge, strengthen the “universal” role of natural sciences, and make them familiar with the interpretation of satellite images. Similar types of landforms on different bodies provided a useful tool to understand phase differences and environmental conditions' role on the realization of various physical/chemical processes.

Introduction

A wide range of surface landforms has been discovered recently by various space missions. Volcanoes, river channels, polar ice caps, dunes, and fallen boulders are present on several planets and moons, among others. Their comparative evaluation could fit into the education of geography and environmental topics for secondary school students. We developed several examples of how properly collected and arranged images help to discover and understand origins and processes beyond the Earth, what also helps to show the general existence of the same physical laws in the Universe.

Methods

During the development of this curriculum, we produced visualization materials (see some example figures in this work) to compare various landforms on different planetary bodies. Used literature based data, the classification of these landforms happened (using unified definitions, listed in the scientific sources), comparison the same types on different bodies happened (to demonstrate similarities and differences, plus link their characteristics to specific local conditions), identification of the formative roles of them (using published results) and also comparison of different groups were done (focusing on the different formative roles and environmental conditions). There were also such landforms whose origin is not clearly known, however listed as candidate formation mode(s). Numerical values were also used and considered, which provide further information on comparisons, beside the context.

Results

Before the developed of the curriculum for planetary science education in Hungary, a classification on review of landforms with specific focus on comparative aspects was originally published in the Encyclopaedia by Sringer (Hargitai and Kereszturi 2015). Opposite to the regular astronomy classes, where various planetary bodies are discussed separately (like presentation of volcanic, tectonic, etc. landforms separately for Venus and separately for Mars), in this curriculum we are discussing various landforms according to groups, for example, all volcanic landforms in one topic or class, all fluvial landforms in another topic or class, etc

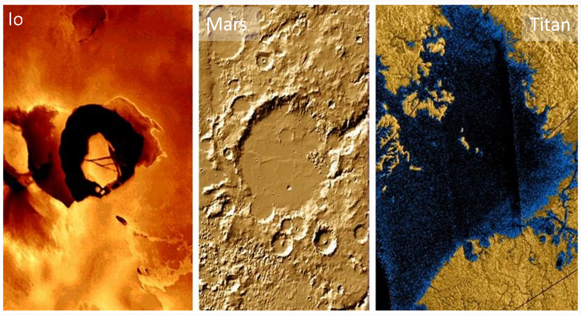
Among the main messages to be given, several important ones are listed below according to the given group of landforms. In an ideal case, the presentation covers geography and physics or astronomy aspects together.

It is important that the basis of discussion uses the geography knowledge from secondary school, what exists at almost all university students. The example topics listed below provide a quick overview of how various landforms should be presented jointly and discussed together. A sample figure to see the similar, analogous nature of the mountain-like elevations from different planets and moons is in a conference proceeding of Kereszturi & Pentek (2012).

Volcanic (and volcanic-like) activity, including the signatures of past activity, can be identified in many object. Volcanic plains can be found on Mercury, Venus, Earth, Moon, Mars, Io, Triton, small parts on Europa and Ganymede, uncertain indications on Ceres and Titan, while active eruptions are going on in the case of the Earth, Io, Enceladus, Triton, and possibly on Venus (where only indirect evidence has been observed yet). A wide range of similarities can be observed, especially among the silicate volcanism-related landforms, including lava flows, lava plains, centralized volcanic elevations, shields and steeper cones, central craters and calderas. The comparative aspects covered: why there are not as large volcanoes on Earth as present on Mars, what is related to the lower gravity (smaller mass), thicker crust, and lack of plate movements above hot spots.

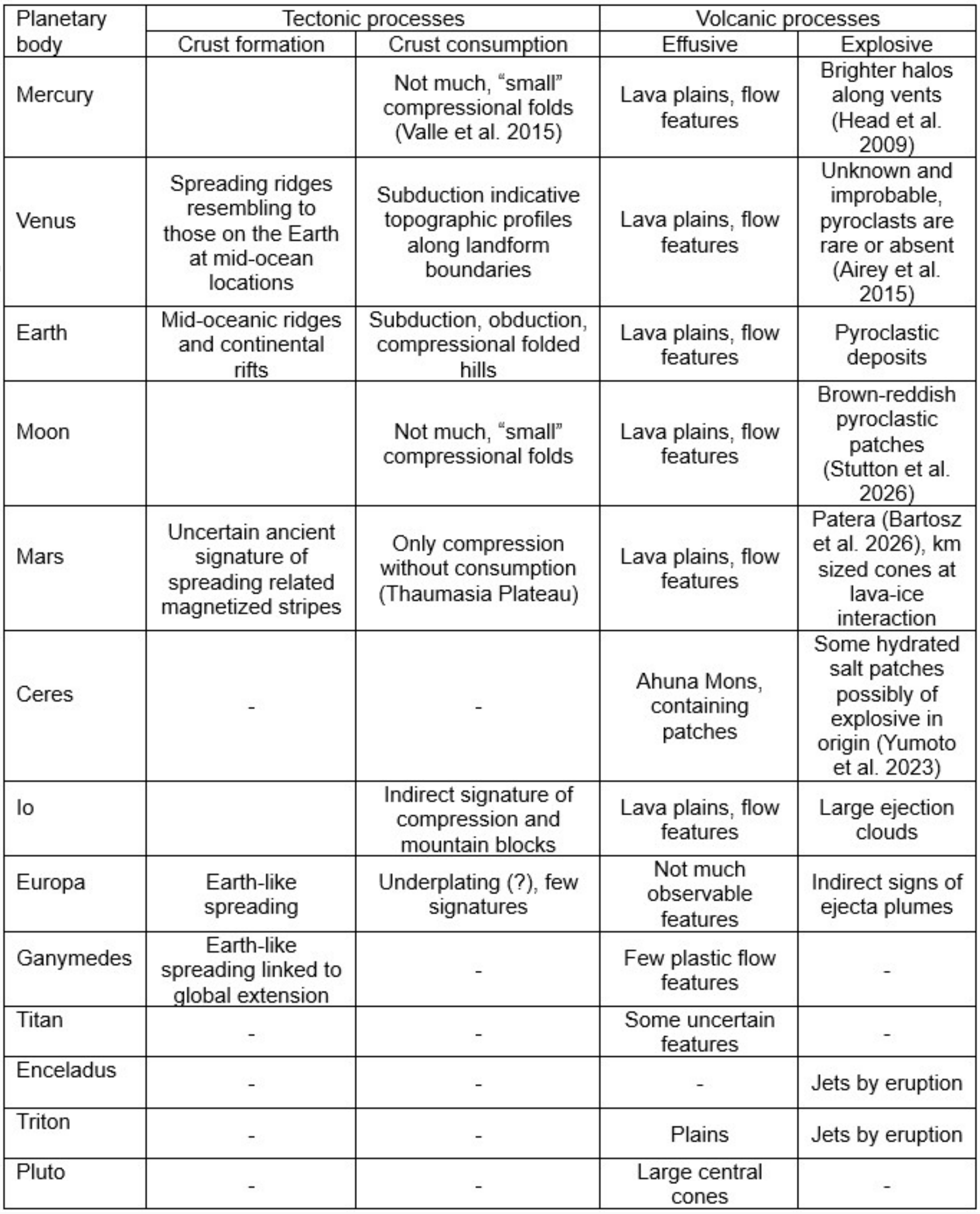
Fluvial features (including valleys, channels, filled lakebeds, delta-like sedimentary features, shorelines, and indications of large standing liquid bodies) were identified on the Earth, Mars, and Titan; while in the last two bodies, most of these landforms are not filled by liquid currently, these features are clearly indicative of liquid flow-like erosion, transport, and deposition in the past. All of these landforms strongly resemble each other in morphology, roughly in physical size, interconnectivity, and context. Important and general physical laws working on all three bodies, which could be presented are:

1. gravity driven movement in a downward direction,
2. Erosion of surface material that cuts elongated depressions,
3. Interconnected and hierarchical network structure that became wider both as channels and valleys by accumulation of liquid discharge in the flow direction,
4. Deposition happens at the decreased surface slope units, producing accumulation there.
5. Fluvial delta features at such locations contain Gilbert-type deltas on Mars, indicating the depth of the formerly existing standing liquid body there.

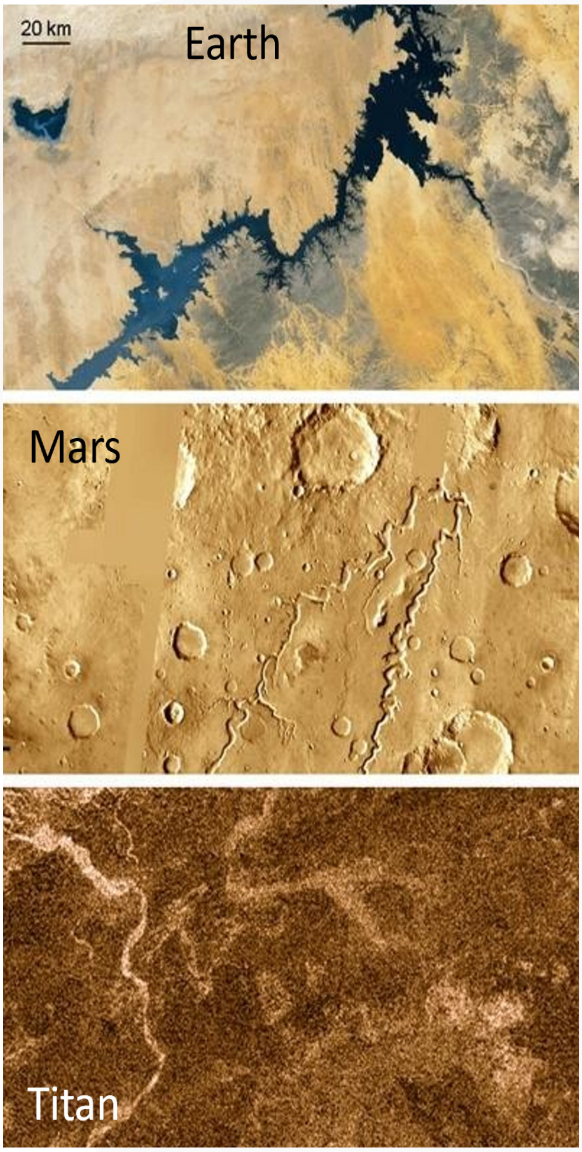


Standing liquid water bodies on Io (lava lake, left), formerly on Mars (lake filled crater, middle), and polar lakes on Titan (right).

Polar caps might exist even on the surface of airless bodies too, where are icy patches in the polar regions at the permanently shadowed locations (depressions without solar illumination ever). There are such features inside the darkest polar craters of Mercury and the Moon.



Planetary body	Tectonic processes		Volcanic processes	
	Crust formation	Crust consumption	Effusive	Explosive
Mercury		Not much, “small” compressional folds (Valle et al. 2015)	Lava plains, flow features	Brighter halos along vents (Head et al. 2009)
Venus	Spreading ridges resembling to those on the Earth at mid-ocean locations	Subduction indicative topographic profiles along landform boundaries	Lava plains, flow features	Unknown and improbable, pyroclasts are rare or absent (Airey et al. 2015)
Earth	Mid-oceanic ridges and continental rifts	Subduction, obduction, compressional folded hills	Lava plains, flow features	Pyroclastic deposits
Moon		Not much, “small” compressional folds	Lava plains, flow features	Brown-reddish pyroclastic patches (Stutton et al. 2026)
Mars	Uncertain ancient signature of spreading related magnetized stripes	Only compression without consumption (Thaumasia Plateau)	Lava plains, flow features	Patera (Bartosz et al. 2026), km sized cones at lava-ice interaction
Ceres	-	-	Ahuna Mons, containing patches	Some hydrated salt patches possibly of explosive in origin (Yumoto et al. 2023)
Io		Indirect signature of compression and mountain blocks	Lava plains, flow features	Large ejection clouds
Europa	Earth-like spreading	Underplating (?), few signatures	Not much observable features	Indirect signs of ejecta plumes
Ganymedes	Earth-like spreading linked to global extension	-	Few plastic flow features	-
Titan	-	-	Some uncertain features	-
Enceladus	-	-	-	Jets by eruption
Triton	-	-	Plains	Jets by eruption
Pluto	-	-	Large central cones	-



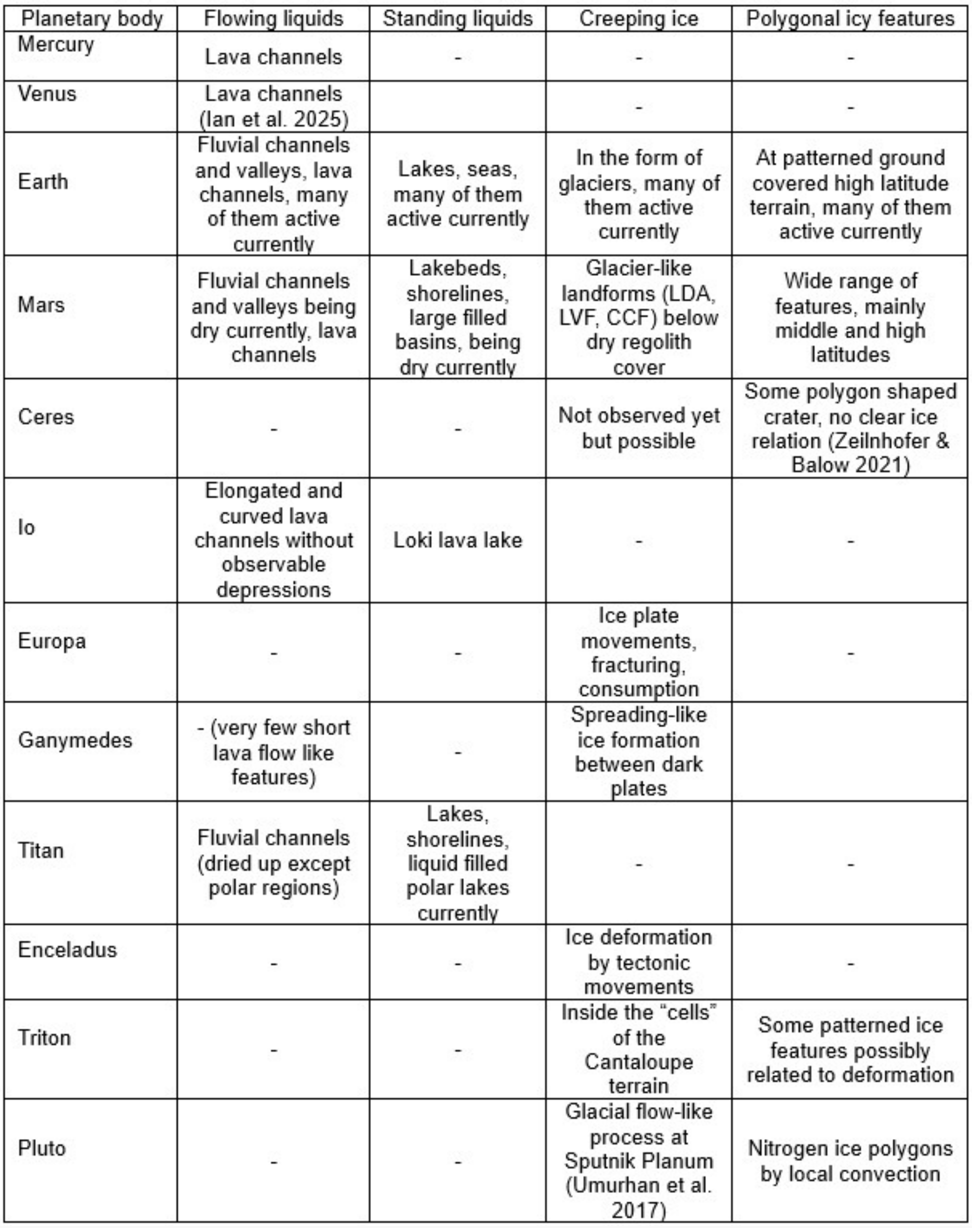
Fluvial channels on Earth (top), Mars (middle) and Tian (bottom) on the same spatial scale.

Here, the weaker illumination and lower polar temperature allow the accumulation and retention of ice. Not a polar cap, but the high-elevation condensation-produced radar-bright mountain “caps” features on Venus, which are composed of certain metals. On this hot body, such elevated melting temperature materials could condense at high-elevation peaks, like high-mountain snow on hills of the Earth.

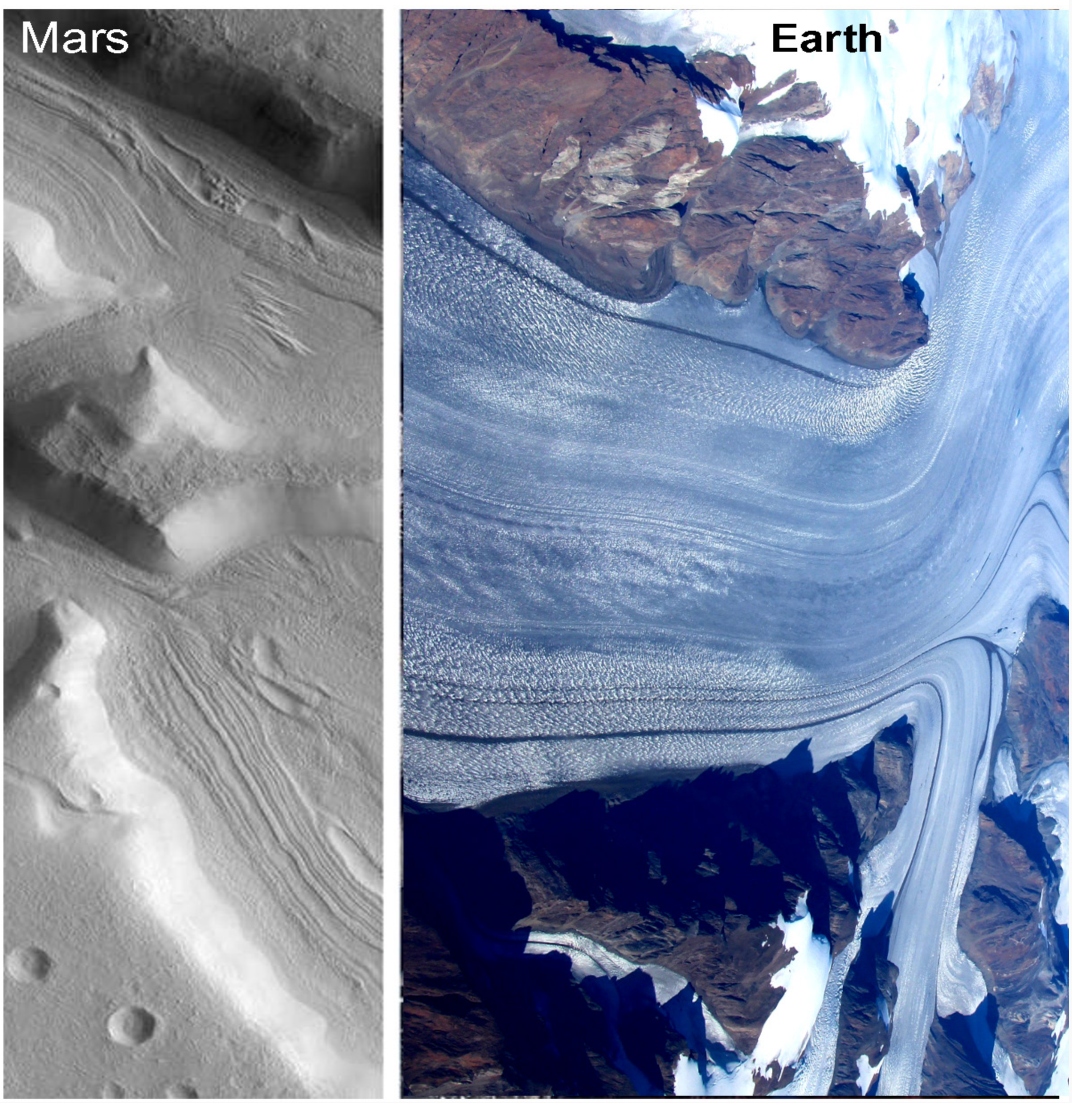
Discussion

In addition to the comparative aspects emerges in the table, the presentation could be arranged into a sequence of order according to the gradual change of various parameters, to demonstrate their role in another way. The following chain of discussions provides some examples of the consequences of variable parameters:

- Role of atmospheric pressure on the rate of explosive versus eruptive styles of volcanic activity. Considering magma with similar temperature and gas content, the explosivity depends on the atmospheric pressure as serves as a closing pressure: in case of large pressure (like Venus) the bubble formation inside ascending magma bodies is supressed, shifting the activity toward an effusive instead of eruptive style. Mars is around the other “end “ of the scale with a larger role of eruptive style, but mainly for the early wet periods, producing large and low shield like paterae.
- Volcanic features show many similarities despite the diverse conditions under which they emerge, including similar characteristics even on airless bodies, indicating that the main driver of landform characteristics is related to the properties of magma and lava, but not the surroundings they erupt into. Gravity also does not influence these landforms much, probably as gravity modifies the speed of magma rising and the flow of lava, but not they main rheological properties what are determined by composition and erupting temperature.



Planetary body	Flowing liquids	Standing liquids	Creeping ice	Polygonal icy features
Mercury	Lava channels	-	-	-
Venus	Lava channels (Ian et al. 2025)		-	-
Earth	Fluvial channels and valleys, lava channels, many of them active currently	Lakes, seas, many of them active currently	In the form of glaciers, many of them active currently	At patterned ground covered high latitude terrain, many of them active currently
Mars	Fluvial channels and valleys being dry currently, lava channels	Lakebeds, shorelines, large filled basins, being dry currently	Glacier-like landforms (LDA, LVF, CCF) below dry regolith cover	Wide range of features, mainly middle and high latitudes
Ceres	-	-	Not observed yet but possible	Some polygon shaped crater, no clear ice relation (Zeilnhofer & Balow 2021)
Io	Elongated and curved lava channels without observable depressions	Loki lava lake	-	-
Europa	-	-	Ice plate movements, fracturing, consumption	-
Ganymedes	- (very few short lava flow like features)	-	Spreading-like ice formation between dark plates	
Titan	Fluvial channels (dried up except polar regions)	Lakes, shorelines, liquid filled polar lakes currently	-	-
Enceladus	-	-	Ice deformation by tectonic movements	-
Triton	-	-	Inside the "cells" of the Cantaloupe terrain	Some patterned ice features possibly related to deformation
Pluto	-	-	Glacial flow-like process at Sputnik Planum (Umurhan et al. 2017)	Nitrogen ice polygons by local convection



Glacier like features on Mars (left) and Earth (right) on similar spatial scale

- The role of temperature on the liquid state of materials could be analysed for Earth, Mars, and Titan. While on Earth bulk-phase liquid water remains in the fluid state at the 0-100 Celsius temperature range, on Mars because of the low average temperature and general humidity, only brines (salty water solutions) remain in the fluid state. On Titan, around -180 Celsius, methane is in the liquid phase, while H2O forms the solid surface. Such comparative aspects improve the understanding of phase states for different material

- The role of gravity in absolute topographic elevation can be seen with the elevation of the largest volcanic cones compared on Earth and Mars in a somewhat complex way. The gravity influences much more the eruption could heights also. While on Io (g=0.18 Earth g), the gravity is much lower than on Earth, causing only a small part of the ejected clouds' material not to fall back to the surface, while on Enceladus (g=0.11 Earth g), a larger part of the jets shoot into space.

Applied aspects emerged in two parts of the curriculum: ArchiSpace project-based regolith evaluation of ISRU activities (Kereszturi et al. 2026), including habitat building, and web-based GIS usage by the students – both topics are discussed elsewhere (Kereszturi, 2026). Several further topics, such as mass movements, have not been covered in this work; however, there are established presentation modes for them. For further information, the author welcomes requests via email from the readers.

Conclusion

Comparative landform analysis was highly useful in explaining the role of environmental parameters for university students. The evaluation of various volcanic, tectonic, fluvial, glacial, and mass wasting produced etc. features not openly widen the knowledge of students but also encourage them to search for further information by themselves. This topic is also ideal for homework, in which students could find and compare various images or even web-GIS-based appearance of different landforms. A further beneficial aspect of landform analysis is that it fits well with both astronomy and Earth science domains at universities.

Acknowledgement

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References

Airey, M. W., Mather, T. A., Pyle, D. M., Glaze, L. S., Ghail, R. C., & Wilson, C. F. (2015). Explosive volcanic activity on Venus: The roles of volatile contribution, degassing, and external environment. *Planetary and Space Science, 113–114*, 33–48.

Bartosz, P., Thomas, J., & Chiedozie, O. C. (2026). Late Amazonian-aged volcanic cones of explosive origin in Ceraunius Fossae, Tharsis, Mars. *Icarus, 445*, 116870.

Flynn, I. T. W., Crown, D. A., Ashley, K. T., & Ramsey, M. S. (2025). Channelized lava flows on Venus: New insights into distribution, morphology, rheology, and emplacement processes. *56th Lunar and Planetary Science Conference*, Abstract 1575.

Head, J. W., Murchie, S. L., Prockter, L. M., Solomon, S. C., Chapman, C. R., Strom, R. G., Watters, T. R., Blewett, D. T., Gillis-Davis, J. J., Fassett, C. I., Dickson, J. L., Morgan, G. A., & Kerber, L. (2009). Volcanism on Mercury: Evidence from the first MESSENGER flyby for extrusive and explosive activity and the volcanic origin of plains. *Earth and Planetary Science Letters, 285*(1–2), 227–242.

Hargitai, H., & Kereszturi, A. (Eds.). (2015). *Encyclopaedia of planetary landforms*. Springer.

Kereszturi, A., & Pentek, K. (2012). New planetary science course at the university of western Hungary. In *43rd Lunar and Planetary Science Conference*. Retrieved in July 2, 2026 from: https://www.lpi.usra.edu/meetings/lpsc2012/pdf/1778.pdf

Kereszturi, A. (2026). Planetary science education in Hungary: Interdisciplinary methods at university level. In *Proceedings of the 3rd International Conference on Universe* (Online, March 4–6, 2026, Abstract #161638).

Kereszturi, A. (2026). Mission planning and planetary science education at ELTE. In *Proceedings of the 9th International Conference on Research, Technology and Education of Space* (Budapest, Hungary).

Kereszturi, A., Ori, G. G., Allemand, P., Bacaoui, A., Bier, H., Ribeiro, T., & Correia, M. (2026). Joint glossary for planetary scientists and architects: Interdisciplinary attempt under the ArchiSpace project. In *Proceedings of the 3rd International Conference on Universe* (Online, March 4–6, 2026, Abstract #28935).

López, V., Ruiz, J., & Vázquez, A. (2015). Evidence for two stages of compressive deformation in a buried basin of Mercury. *Icarus, 254*, 18–23.

Sutton, S. R., Lanzirotti, A., Newville, M., Dyar, M. D., & McCanta, M. (2026). Complex redox histories of lunar pyroclastic beads revealed by spatially correlated chromium and vanadium valences. *Journal of Geophysical Research: Planets, 131*(5), e2025JE009416.

Umurhan, O. M., Howard, A. D., Moore, J. M., Earle, A. M., White, O. L., Schenk, P. M., Binzel, R. P., Stern, S. A., Beyer, R. A., Nimmo, F., McKinnon, W. B., Ennico, K., Olkin, C. B., Weaver, H. A., & Young, L. A. (2017). Modeling glacial flow on and onto Pluto's Sputnik Planitia. *Icarus, 287*, 301–319.

Yumoto, K., Cho, Y., Koyaguchi, T., & Sugita, S. (2023). Dynamics of gas-driven eruption on Ceres as a probe to its interior. *Icarus, 400*, 115533.

Zeilnhofer, M. F., & Barlow, N. G. (2021). The characterization and distribution of polygonal impact craters on Ceres and their implications for the Cerean crust. *Icarus, 368*, 114586.

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Cosmic Strings: Lecture Notes

Özlem Yeşiltaş

Introduction

Cosmic strings are one-dimensional topological defects that may have formed during phase transitions in the early Universe. They arise when a continuous symmetry is spontaneously broken, leaving a vacuum manifold with non-trivial topology.

The study of cosmic strings combines ideas from classical field theory, topology, cosmology, and general relativity. Their existence depends not only on the local dynamics of a field theory but also on the global properties of the vacuum manifold.

One of the most remarkable features of cosmic strings is their gravitational effect. Unlike ordinary massive objects, an ideal cosmic string produces a conical spacetime geometry characterized by a deficit angle rather than a Newtonian gravitational potential.

The purpose of these notes is to introduce the basic concepts underlying cosmic strings, including spontaneous symmetry breaking, phase transitions, topological defects, and their geometrical properties.

Symmetry Breaking and the Sombrero Potential

A fundamental concept in modern field theory is spontaneous symmetry breaking. Consider a complex scalar field ϕ with the potential

$$V(\phi) = \frac{\lambda}{4}\left(|\phi|^2 - \eta^2\right)^2, \qquad (1)$$

where $\lambda > 0$ is a coupling constant and η is the vacuum expectation value. This potential is known as the Mexican Hat Potential or Sombrero Potential. The theory is invariant under the global $U(1)$ transformation

$$\phi \to e^{i\alpha}\phi. \qquad (2)$$

The minima of the potential satisfy

$$|\phi| = \eta. \qquad (3)$$

Therefore the vacuum states are given by

$$\phi_{\text{vac}} = \eta e^{i\theta}, \qquad (4)$$

where θ is an arbitrary angle. The set of all vacuum states forms a circle,

$$\mathcal{M} = S^1, \qquad (5)$$

called the vacuum manifold. The term manifold is used because the set of degenerate vacuum states has a smooth geometrical structure. In the present model, the complex scalar field can be written in polar form as

$$\phi = \rho e^{i\theta}, \qquad (6)$$

where $\rho = |\phi|$ is the radial magnitude of the field and θ is its phase. The potential depends only on the magnitude $|\phi|$ and not on the phase θ. Therefore all field values with the same magnitude $|\phi| = \eta$ have exactly the same minimum energy. Geometrically, the condition

$$|\phi| = \eta \qquad (7)$$

defines a circle of radius η in the complex ϕ-plane. Thus the vacuum manifold is not the full complex plane, but only the circle of minima,

$$\mathcal{M} = \{\phi \in \mathbb{C} \;:\; |\phi| = \eta\}. \qquad (8)$$

This set is topologically equivalent to the unit circle S^1. Therefore one writes

$$\mathcal{M} \simeq S^1. \tag{9}$$

The symbol $\simeq$ indicates that the vacuum manifold has the same topology as a circle, although its radius is η rather than one. This geometrical structure is essential for the existence of cosmic strings. If the vacuum manifold consisted of only a single point, then every field configuration could be continuously deformed into the same vacuum. In that case no stable topological string defect would appear. However, when the vacuum manifold is a circle, the phase of the scalar field may wind around this circle. Along a closed curve in physical space, the phase may change as

$$\theta \to \theta + 2\pi n, \tag{10}$$

where n is an integer. This integer is called the winding number. The possibility of non-zero winding is a topological property of the vacuum manifold. It is expressed by the fundamental group

$$\pi_1(S^1) = \mathbb{Z}. \tag{11}$$

This means that closed loops on the vacuum manifold are classified by an integer. A loop with $n = 0$ can be continuously contracted to a point, whereas a loop with $n \neq 0$ winds around the circle and cannot be removed without leaving the vacuum manifold. For a cosmic string, this has a direct physical meaning. Far from the string core, the field lies on the vacuum manifold, but as one moves once around the string in physical space, the phase of the field winds around the vacuum circle. At the center of the string, the phase becomes ill-defined. To avoid a singular field configuration, the magnitude of the field must go to zero,

$$\phi(0) = 0. \tag{12}$$

Therefore the field leaves the vacuum manifold at the string core. The core is the region where the symmetry is locally restored.

Although the potential possesses a continuous rotational symmetry, the system eventually chooses one particular vacuum state. This process is called spontaneous symmetry breaking. An intuitive analogy is a ball balanced at the top of a sombrero-shaped hill. The top position is perfectly symmetric but unstable. Once the ball rolls down, it chooses a specific direction and the symmetry is broken.

Cosmological Phase Transitions

In the very early Universe, temperatures were extremely high and many symmetries were restored. As the Universe expanded, its temperature decreased and the effective potential changed its shape. A simple temperature-dependent potential can be written schematically as

$$V(\phi, T) = \frac{\lambda}{4}\left(|\phi|^2 - \eta^2(T)\right)^2. \tag{13}$$

At sufficiently high temperatures the minimum is located at

$$\phi = 0, \tag{14}$$

which preserves the symmetry. Below a critical temperature T_c, the symmetric state becomes unstable and the minimum moves away from the origin. The field must then select one of infinitely many degenerate vacuum states. This phenomenon is known as a cosmological phase transition. The situation is similar to the spontaneous magnetization of a ferromagnet below its Curie temperature. Above the critical temperature all directions are equivalent. Below the critical temperature a preferred direction emerges.

Topological Defects

When the Universe was extremely hot, fundamental symmetries were unbroken and the scalar field occupied a unique symmetric state. As the Universe expanded and cooled below a critical temperature, spontaneous symmetry breaking occurred and the field settled into one of many energetically equivalent vacuum states. Since information cannot propagate faster than the speed of light, distant regions of the Universe were unable to coordinate their choice of vacuum. Consequently, different regions selected different vacuum states independently.

This simple fact has remarkable consequences. When neighbouring regions with different vacuum choices meet, the scalar field cannot always vary smoothly everywhere. In certain locations, discontinuities or non-trivial field configurations remain trapped. These stable configurations are known as topological defects. Their formation mechanism was first proposed by Tom Kibble and is now known as the Kibble mechanism.

The existence of a topological defect is determined entirely by the topology of the vacuum manifold

$$\mathcal{M} = G/H, \tag{15}$$

where G is the original symmetry group and H denotes the subgroup that remains unbroken after the phase transition.

Different topological properties of the vacuum manifold give rise to different types of defects. The classification is provided by the homotopy groups of $\mathcal{M}$:

Group	Defect	Dimension
$\pi_0(\mathcal{M})$	Domain Walls	2D
$\pi_1(\mathcal{M})$	Cosmic Strings	1D
$\pi_2(\mathcal{M})$	Monopoles	Point-like
$\pi_3(\mathcal{M})$	Textures	Non-local

Each homotopy group describes a different type of topological obstruction. If the corresponding homotopy group is non-trivial, the field configuration cannot be continuously deformed into the vacuum state without leaving the vacuum manifold. As a result, the defect is topologically stable.

Domain Walls

Domain walls arise when the vacuum manifold consists of disconnected components. A simple example is the spontaneous breaking of a discrete symmetry,

$$\phi \to -\phi, \tag{16}$$

which possesses two equivalent vacuum states,

$$\phi = \pm\eta. \tag{17}$$

Neighbouring regions may settle into different minima, producing a two-dimensional interface known as a domain wall.

Cosmic Strings

Cosmic strings appear when the vacuum manifold contains non-contractible closed loops,

$$\pi_1(\mathcal{M}) \neq 0. \tag{18}$$

For the symmetry breaking

$$U(1) \to 1, \tag{19}$$

the vacuum manifold becomes

$$\mathcal{M} = S^1, \tag{20}$$

whose fundamental group is

$$\pi_1(S^1) = \mathbb{Z}. \tag{21}$$

The scalar field may therefore wind around the vacuum manifold an integer number of times. This winding number cannot change continuously, making the string topologically stable.

Magnetic Monopoles

Magnetic monopoles are point-like defects associated with a non-trivial second homotopy group,

$$\pi_2(\mathcal{M}) \neq 0. \tag{22}$$

A well-known example occurs in certain Grand Unified Theories, where

$$SU(2) \to U(1). \tag{23}$$

In this case the vacuum manifold is topologically equivalent to a sphere,

$$\mathcal{M} \simeq S^2, \tag{24}$$

and

$$\pi_2(S^2) = \mathbb{Z}. \tag{25}$$

The existence of monopoles is one of the classic predictions of Grand Unified Theories.

Textures

Textures correspond to non-trivial mappings characterized by

$$\pi_3(\mathcal{M}) \neq 0. \tag{26}$$

Unlike cosmic strings or monopoles, textures are not localized objects. Instead, they are large-scale field configurations that gradually unwind as the Universe evolves. Although they do not possess a stable core, they may leave observable signatures in the cosmic microwave background.

Topological Stability

The stability of these defects is fundamentally geometric rather than dynamical. A configuration carrying a non-zero topological charge cannot be continuously transformed into the vacuum without forcing the field to leave the vacuum manifold. This would require passing through regions of higher potential energy where the symmetry is locally restored.

For this reason, topological defects are often described as topological solitons: their stability is guaranteed not by forces, but by the topology of the vacuum manifold itself.

Cosmic Strings and Homotopy

Cosmic strings appear when the vacuum manifold possesses a non-trivial fundamental group,

$$\pi_1(\mathcal{M}) \neq 0. \tag{27}$$

For the symmetry breaking

$$U(1) \to 1, \tag{28}$$

the vacuum manifold is

$$\mathcal{M} = S^1. \tag{29}$$

The corresponding homotopy group is

$$\pi_1(S^1) = \mathbb{Z}. \tag{30}$$

This result implies that field configurations may wind around the vacuum manifold an integer number of times. The winding number is defined as

$$n = \frac{1}{2\pi} \oint d\theta. \tag{31}$$

Configurations with different values of n cannot be continuously deformed into one another. Consequently, the defect is topologically stable. These stable one-dimensional defects are called cosmic strings. Far from the string core, the scalar field approaches a vacuum state,

$$|\phi| \to \eta, \qquad r \to \infty. \tag{32}$$

At the center of the defect,

$$\phi(0) = 0. \tag{33}$$

Thus the symmetry is restored inside the string core.

Gravitational Geometry of a Cosmic String

An ideal straight cosmic string generates the space-time metric

$$ds^2 = -dt^2 + dr^2 + \alpha^2 r^2 d\varphi^2 + dz^2, \quad (34)$$

where

$$\alpha = 1 - 4G\mu. \quad (35)$$

Here μ denotes the string tension and G is Newton's gravitational constant. This metric is locally flat but globally conical. The corresponding deficit angle is

$$\Delta = 8\pi G\mu. \quad (36)$$

The conical geometry produces characteristic gravitational lensing effects and represents one of the most important observational signatures of cosmic strings.

String Tension and Mass Density

The parameter μ denotes the energy per unit length of the cosmic string and is commonly referred to as the string tension. In relativistic units ($c = 1$), energy and mass are equivalent, and therefore μ may also be interpreted as the mass per unit length of the string. In SI units,

$$[\mu] = \frac{\text{kg}}{\text{m}} \text{ or } \frac{\text{J}}{\text{m}}. \quad (37)$$

Thus a cosmic string is characterized by an enormous concentration of mass along an effectively one-dimensional object. For strings formed at a symmetry-breaking scale η, dimensional arguments suggest

$$\mu \sim \eta^2. \quad (38)$$

We can also look at $G\mu$, which measures the strength of the gravitational field. For GUT cosmic strings, one typically finds

$$G\mu \sim 10^{-6}. \quad (39)$$

Current observational constraints suggest smaller values,

$$G\mu \lesssim 10^{-7} - 10^{-11}, \quad (40)$$

depending on the specific model. The deficit angle generated by an ideal cosmic string is

$$\Delta = 8\pi G\mu. \quad (41)$$

For example, if

$$G\mu = 10^{-6}, \quad (42)$$

then

$$\Delta \simeq 2.5 \times 10^{-5} \text{ rad} \approx 5'', \quad (43)$$

corresponding to an angular separation of a few arcseconds. Although this angle is small, it is sufficiently large to produce observable gravitational lensing signatures. The linear mass density associated with a GUT-scale cosmic string is enormous. Using SI units one obtains approximately

$$\mu \sim 10^{21} \text{ kg} \cdot \text{m}^{-1}, \quad (44)$$

meaning that one meter of cosmic string may contain a mass comparable to that of a large asteroid.

Global and Local Cosmic Strings

Cosmic strings can be studied in two main classical field-theoretical settings: global strings and local strings. For a global $U(1)$ symmetry, the Lagrangian density of a complex scalar field may be written as

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - V(\phi). \quad (45)$$

A straight static cosmic string aligned with the z-axis is described by the ansatz

$$\phi(r,\varphi) = \eta f(r) e^{in\varphi}, \tag{46}$$

where n is the winding number and $f(r)$ is a radial profile function. The boundary conditions are

$$f(0) = 0, \qquad f(\infty) = 1. \tag{47}$$

These conditions express the fact that the field vanishes at the string core and approaches the vacuum far from the core. In a local $U(1)$ theory, the scalar field is coupled to a gauge field A_μ. The corresponding Abelian Higgs model is

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\phi)^*(D^\mu\phi) - \frac{\lambda}{4}\left(|\phi|^2 - \eta^2\right)^2, \tag{48}$$

where

$$D_\mu = \partial_\mu - ieA_\mu \tag{49}$$

is the gauge-covariant derivative and

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \tag{50}$$

is the electromagnetic-type field strength. The local string solution is known as the Nielsen–Olesen vortex. A standard ansatz is

$$\phi(r,\varphi) = \eta f(r) e^{in\varphi}, \tag{51}$$

$$A_\varphi(r) = \frac{n}{e} a(r). \tag{52}$$

The profile functions satisfy

$$f(0) = 0, \qquad a(0) = 0, \tag{53}$$

and

$$f(\infty) = 1, \qquad a(\infty) = 1. \tag{54}$$

The scalar field determines the symmetry-breaking structure, while the gauge field regularizes the energy of the string. Thus the Nielsen–Olesen vortex provides the basic classical field-theoretical model of a cosmic string.

String Tension and Deficit Angle

The energy per unit length of a cosmic string is called the string tension and is denoted by μ. It is obtained by integrating the energy density over the plane perpendicular to the string,

$$\mu = \int T_{00}\, d^2x. \tag{55}$$

For an ideal straight string, this tension acts as the source of the conical spacetime geometry. The gravitational effect of the string is therefore encoded not in a Newtonian potential but in the angular deficit

$$\Delta = 8\pi G\mu. \tag{56}$$

This is one of the most characteristic classical signatures of cosmic strings. A light ray passing near an ideal string is not attracted in the usual Newtonian sense. Instead, the global conical structure of space-time can produce double images of a background object.

Physical Interpretation

The formation of a cosmic string can be summarized as follows. During a phase transition, the scalar field chooses different vacuum phases in different regions of space. Around certain closed paths, the phase may wind by an integer multiple of 2π. If this winding cannot be removed continuously, a topologically stable defect remains.

The center of the defect corresponds to a region where the scalar field must leave the vacuum manifold. Therefore the field vanishes at the core and the symmetry is restored locally. Away from the core, the field approaches the broken-symmetry vacuum.

In this way, cosmic strings provide a direct connection between spontaneous symmetry breaking, topology, classical field theory and general relativity.

Conclusion

Cosmic strings are topologically stable one-dimensional defects that may form during cosmological phase transitions. Their existence is intimately related to spontaneous symmetry breaking, the topology of the vacuum manifold, and the presence of non-trivial homotopy groups.

In addition to their significance in classical field theory, cosmic strings provide a fascinating connection between topology, gravitation, and cosmology.

References

Copeland, E. J., & Kibble, T. W. B. (2010). Cosmic strings and superstrings. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 466(2115), 623–657.

Hindmarsh, M., & Kibble, T. W. B. (1995). Cosmic strings. Reports on Progress in Physics, 58(5), 477–562.

Kibble, T. W. B. (1976). Topology of cosmic domains and strings. Journal of Physics A: Mathematical and General, 9(8), 1387–1398.

Manton, N., & Sutcliffe, P. (2004). Topological solitons. Cambridge University Press.

Nakahara, M. (2003). Geometry, topology and physics (2nd ed.). CRC Press.

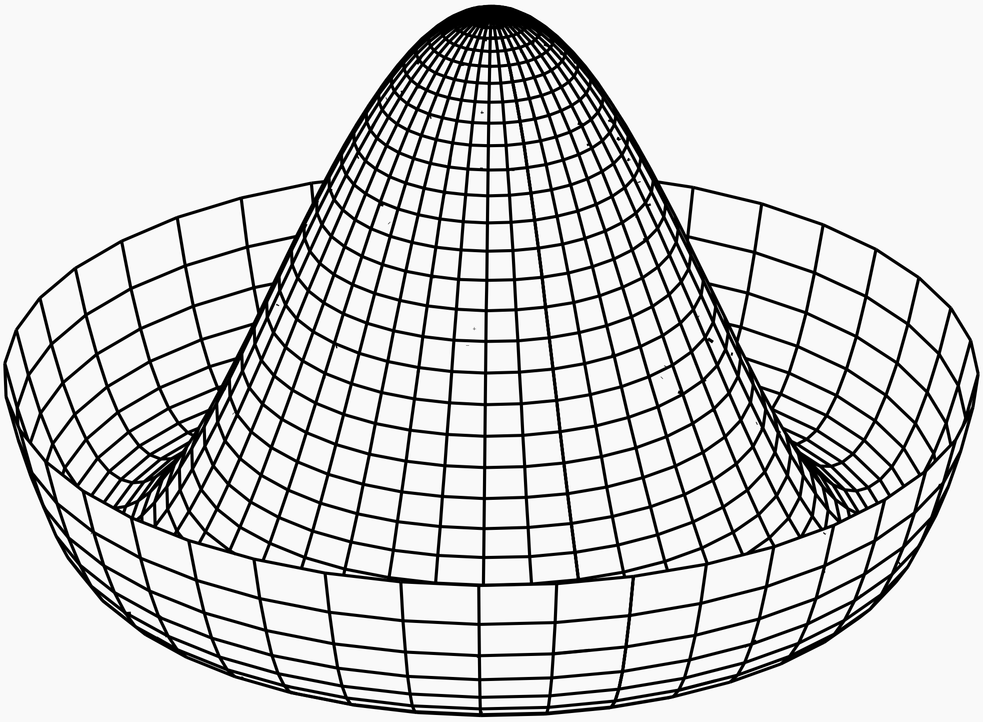
Nielsen, H. B., & Olesen, P. (1973). Vortex-line models for dual strings. Nuclear Physics B, 61, 45–61.

Rajaraman, R. (1982). Solitons and instantons. North-Holland.

Tong, D. (2005). TASI lectures on solitons. arXiv. https://arxiv.org/abs/hep-th/0509216

Vilenkin, A., & Shellard, E. P. S. (1994). Cosmic strings and other topological defects. Cambridge University Press.

Weinberg, S. (1996). The quantum theory of fields: Volume 2, Modern applications. Cambridge University Press.



Graph of sombrero potential V(ϕ)