swiss physical society

Nr. 78, März 2026

SPG Mitteilungen
Communications de la SSP

Auszug - Extrait

Progress in Physics (111)

The power of small telescopes: science and sustainability

Aurora Sicilia-Aguilar and Paula S. Teixeira, University of Dundee, UK

DOI: *10.5281/zenodo.18716819*

Progress in Physics (111)

The power of small telescopes: science and sustainability

Aurora Sicilia-Aguilar and Paula S. Teixeira, University of Dundee, UK

In the quest for larger telescopes, we may still want to properly acknowledge the humbler yet powerful ground-based, small counterparts. Such telescopes still have much to offer, in particular, we profit from their wide fields of view, their time availability, and also their lower monetary and environmental impact costs.

Understanding star and planet formation

Star and planet formation are two sides of the same problem: in the fight between gravitation and thermal pressure that shapes the gas clouds in our galaxy and beyond, a star will form when gravity wins and a denser lump in the cloud collapses. Evolution from a pre-stellar core to a protostar, and eventually, a star, involves a contraction by 6 orders of magnitude in size in a timescale well below one million years. Conservation of angular momentum thus leads to the formation of a young star surrounded by a protoplanetary disk (Fig. 1). This disk eventually disperses, leaving behind a newly-formed planetary system.

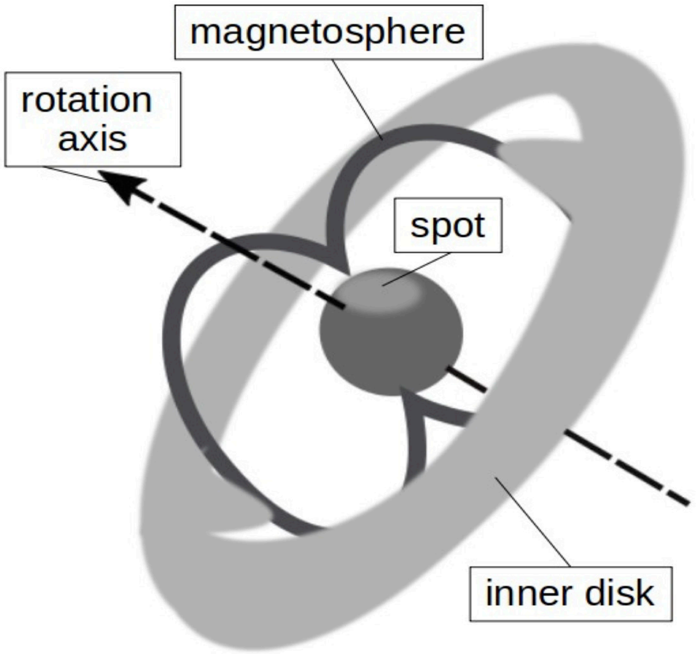

Fig. 1. A cartoon of the innermost regions of a young star (not to scale; a disk would extend over the size of a Solar System, while the magnetosphere is typically a few stellar radii). The magnetic field of the star disrupts the disk and channels accretion, which creates a hot spot on the stellar surface. Stellar spots produce variability as the star rotates, and material lifted from the disk can obscure the star, producing "dips".

For those of us living in the habitable zone around the Sun, looking for other nascent systems in nearby star-forming regions is the way to try to reconstruct the history of our own system, as well as to estimate the chances of forming similar planets. But observing these systems is exceedingly challenging. While a protostar in a nearby star-forming region may have an angular size comparable to a few percent of the diameter of the full Moon, and a disk would be comparable to a 1.5 km crater, a star would be the size of a volley ball lying in one of the craters, and the habitable zone of the disk would be barely the size of a volleyball court... Moreover, most nearby star-forming regions are probably not analogues to where the Sun formed. Exploring more distant regions is thus equivalent to looking at a small marble sitting in the middle of a hula ring, all based on the Moon.

Interferometers can nowadays resolve the innermost regions of some star-planet systems. Optical interferometry can map accretion columns, albeit mostly for bright stars that are often not solar analogues, and with lengthy (and costly) observations. Submillimeter data can also resolve protoplanetary disks, but most objects are not resolved beyond what would be equivalent to the orbit of Jupiter, since the inner disk is small, faint, and relatively warm. The inner disk is too faint in the submillimeter even for interferometers such as ALMA, and spectropolarimetry or IR interferometry can only target few close, bright stars, very different from the Sun, so that statistical studies of the inner regions of nascent planetary systems are thus lacking.

In the task of putting the Solar System into context, we also note that not all systems evolve in the same way. This means statistics are needed, covering as many stars as possible, with different ages, initial conditions, and environments. Because not all nearby star forming regions are analogues to the one in which our Sun formed, nor cover the entire age range to visualize the process, we need to probe distances further out. Away from bright objects and beyond the limits of interferometry.

Tracking small scales: *Using time to map space*

The power of alternative observational methods, going beyond the spatial resolution of imaging, has been long noticed. It is not by chance that many recent missions are built around making the most of repeated observations, from the Gaia Mission to map the Milky Way [1], to the Vera Rubin Observatory [2]: the focus has shifted onto *using time to map space*.

Time is able to turn around the problem posed by spatial (or angular) resolution. Small scales that are hard to resolve in images are also the ones that display changes with the shortest temporal cadences. Often, short enough to be comparable to human timescales (Fig. 2). Time resolution is not only a powerful tool to investigate tiny structures: In fact, when dealing with the very small spatial scales around young stars, *using time to map space* is the only feasible method to study statistically significant numbers of sources, especially for the normally faint solar analogues.

Timescales in the surroundings of forming stars range from the few days of typical stellar rotation, to the few years comprising the Keplerian orbit of a protoplanetary disk fragment at a couple of astronomical units' distance (Fig. 2). The

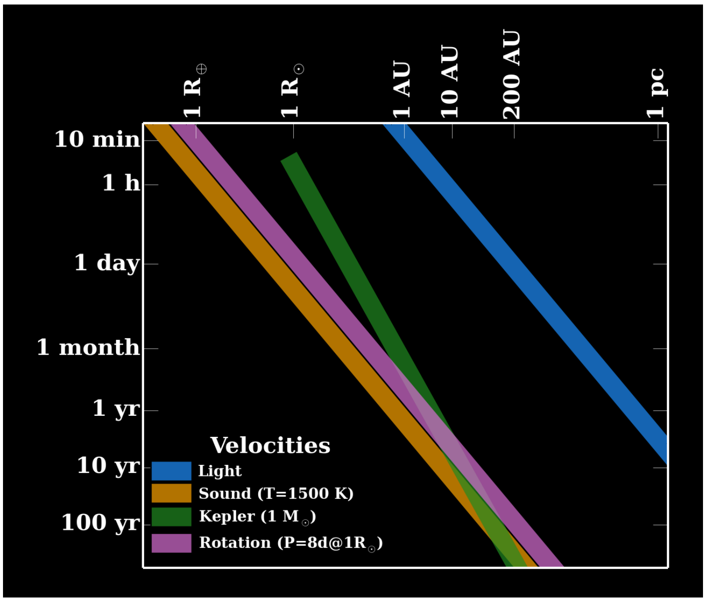

Fig. 2. Using time to map space. How fast different signals can cover distances ranging from Earth's radius to interstellar distances.

spots, hot or cold, on the stellar surface, and the irregularities of the inner disk that may be related to planets, cross our line-of-sight creating different patterns on the measured luminosity of a star and thus revealing what cannot be resolved in an image. Travel time also depends on what is moving: Whether it is light casting a shadow, or a stellar or planetary rotation, or a sound wave propagating in the circumstellar medium. The relation between the size of a region and how rapidly it changes, means that to detect stellar rotation, we may just observe for a few weeks and that by gathering observations over a few years, we can picture changes in the parts of the disk that will give rise to planets in the habitable zone.

An example: The North-PHASE Legacy Survey

North-PHASE stands for "*Periodicity, Hot spots, Accretion Stability and Early evolution in young stellar clusters in the northern hemisphere*" and it is a 5-year (2023 - 2028) Legacy Survey at the Javalambre Observatory (Spain), led by the University of Dundee [3]. Using time-resolved, multi-cadence, multiwavelength, large field data, it is unveiling structures and processes in young stars at the relevant scales for inner planet formation, while also studying the connection between stars, their formation history, and their clusters, independently of astrometry. North-PHASE is unique at *using time to map space* thanks to the combination of filters that allow to investigate the temperature of stars and spots and the material properties of the inner disks, while covering thousands of young stars in each shot for a statistical study of their variability and the physical processes to which it is linked. And it is also unique because of its wide-field camera [4,5].

North-PHASE produces stunning wide-field images, each covering about 10 times the size of the full Moon and providing multi-color data on hundreds of thousands of stars (Fig. 3). Hidden within the beauty of the large-field images are the technical details, such as an extremely robust coordinate solution over the entire large field and an amazing CCD stability that is allowing us to detect variability down to below 1% - and all this with a ground-based, 83 cm telescope. The irregular observing cadence of North-PHASE can measure rotational periods of thousands of stars, including many young solar twins of different ages, and the current two years of data are already revealing variations in the spots that betray stellar rotation, as well as in the disks that surround them.

By observing each star more than a hundred times per year, we can track luminosity variations below 1 part in 100 and explore the mechanisms behind the changes. In some stars, sinusoidal curves reveal rotation of a star with a spot, and the multiple photometric bands allow us to track the size and temperature of the spot(s). In others, we discover that the protoplanetary disk is not as flat as one would expect, causing eclipses that repeat themselves in a semi-regular pattern. These eclipses can be pinpointed to a location in the disk where some perturbations (accreting material, winds, or maybe nascent planets) lift the dusty disk surface to obscure the star (Fig. 4). And such examples are only the beginning: the complexity and diversity of the available data is now at a stage where citizen science can make a key contribution to the analysis.

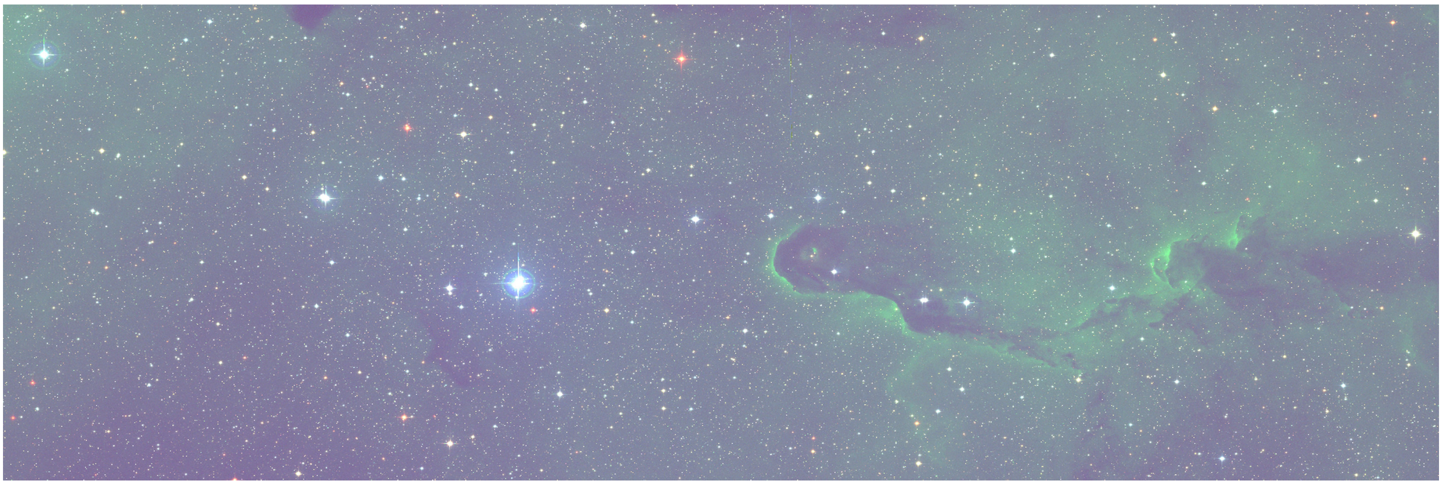

Fig. 3. A view of the Tr37 cluster and the surrounding IC1396 nebula taken by North-PHASE. The region is located at 920 pc (3000 light years). Colors represent different filters, with g (470 nm) being blue, J0660 (covering the Hydrogen alpha line at 656 nm) in green, and z (890 nm) in red. Only about 1/5 of the very large image is displayed here.

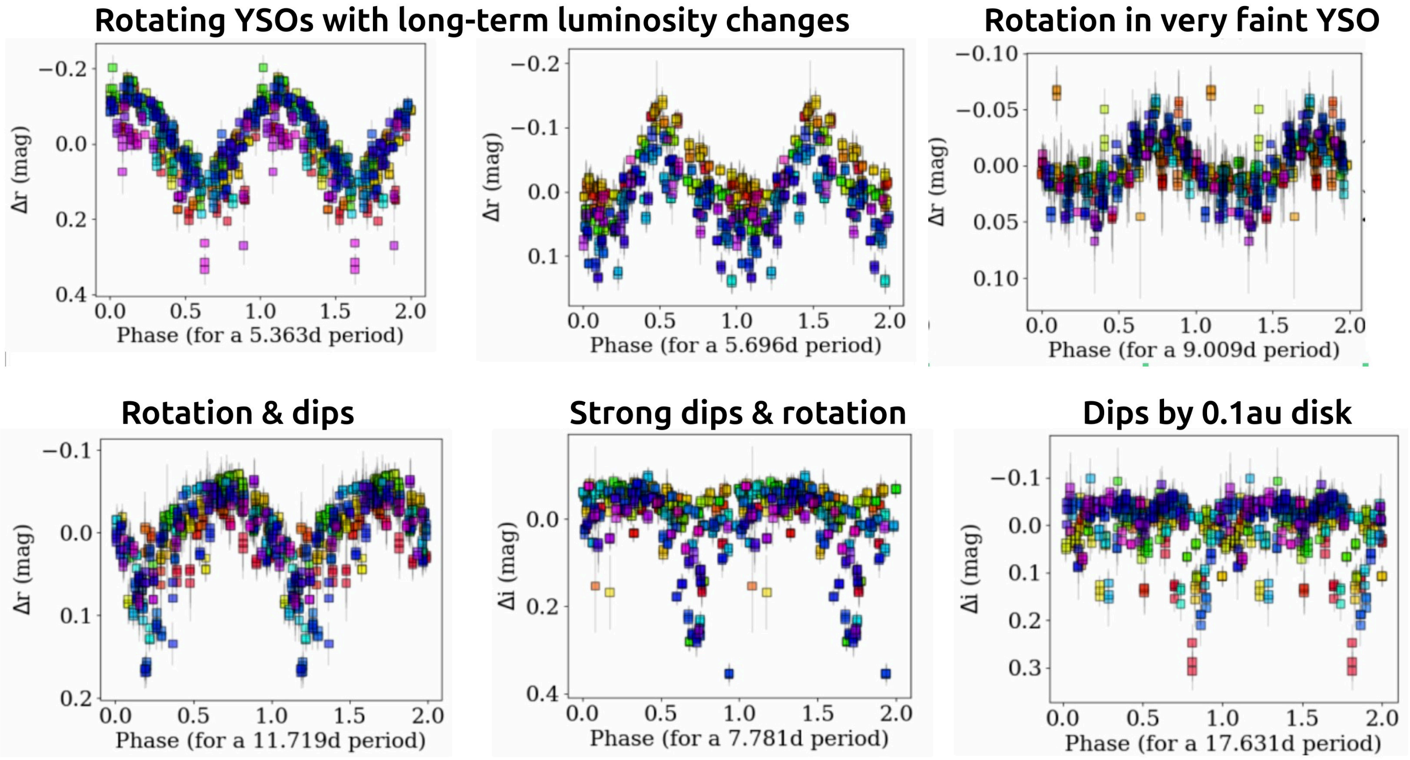

Fig. 4. Several of the variable stars identified by North-PHASE during its first 2 years. The data is presented as changes in brightness folded to account for the periodicity (phase space for the given period, plotted twice). The color scheme marks the time evolution, from red to violet. Brighter magnitudes are smaller, hence negative changes correspond to the star getting brighter. Only one of the 6 filters available is shown per star. Examples show sinusoidal curves due to rotation of stars with a spot and dips caused by disk material near the star or further out.

Small telescopes and the quest for sustainable astronomy

The North-PHASE Legacy Survey represents a step toward more sustainable astronomical research, demonstrating how high-impact science can be achieved with reduced environmental cost. Operating from the Javalambre Observatory (OAJ) with a modest 83 cm ground-based telescope, the survey fully leverages the scientific potential of low-carbon infrastructure. Smaller telescopes require substantially fewer construction materials, reduced land disturbance, and lighter ongoing operational loads, allowing them to deliver competitive scientific output while generating a fraction of lifetime emissions. This structural advantage is reflected directly in the OAJ's comparatively low annual electricity consumption (600 MWh in 2021; [6]), which remains far below that of major facilities.

OAJ further advances sustainability by integrating renewable energy systems directly into its operations. Its 200 kW solar array provides 50% energy self-sufficiency, reducing dependence on carbon-intensive grid electricity, while geothermal systems supply 73% of heating and cooling needs [6], sharply curbing emissions associated with climate control, historically one of the most energy-demanding aspects of observatory operations. These systems not only reduce carbon output but also enhance operational resilience and demonstrate a scalable template for sustainable facility design.

At a broader level, sustainable astronomy requires a structural shift away from constant investment in new, massive research infrastructures that lock in emissions for decades through construction, global supply chains, and high-intensity operations [7]. Facilities like the OAJ embody an alternative paradigm: modern design principles that prioritize efficiency, modularity, and minimal resource use. The automated control systems developed for smaller observatories [8,9] explicitly aim to maximize operational efficiency while reducing routine maintenance, material throughput, and human intervention. By reducing commuting and professional flights, which are activities recognized as among the most carbon-intensive within the astronomical profession [10], the OAJ's operational model mitigates one of the field's most challenging emissions sources.

Moreover, multi-year photometric legacy surveys such as North-PHASE generate extensive datasets that form high-value, long-lived scientific archives. These archives allow repeated exploitation of existing observations, multiplying the scientific return per unit of energy and material invested [11]. By enabling large-scale time-domain studies without requiring additional observational cost, archival science maximized the scientific yield per unit of energy and material invested. This highly efficient use of resources directly addressed the subsequent imperative of data recycling and reducing the technical debt, focusing on developing tools that allow the community to explore and analyze existing data.

Data recycling and reducing the technical debt

If we want to go forward in the quest of making astronomy more sustainable, we need to consider that telescope databases are full of data, some of which were not used to the extent originally intended due to various reasons - finding the unexpected and lacking enough time to go in depth within the extremely hectic research and teaching world is one of them. Data wasting, similar to food wasting, generates a large CO_2 footprint without proving much benefit. Thus, creating tools that allow us to explore and analyze existing data down to its deepest possibilities is also an important part of making astronomy sustainable.

One example is the substantial amount of spectroscopic data that was acquired with the intention of finding radial velocity planets around young stars. While initially expected that the processes around the star, such as accretion, would be eminently stochastic and thus different from the stable signatures of planets, this was found to not be the case, and the task of finding the planets became technically unfeasible. But if the signatures of forming stars were so robust and regular, why not use them instead to disentangle the way stars connect to their disks? With the creation of the STAR-MELT public Python package [12,13], we enabled the existing spectral data, from about any high-resolution spectroscope from the major observatories, to be easy to analyze and combine, extracting emission lines that reveal the location and time variability of the footprints of accretion columns on the stellar surface.

Therefore, additional community work towards the creation of tools that facilitate the analysis and recycling of existing data is also a valuable tool to reduce the technical debt as well as the carbon footprint of astronomy. Comprehensive exploitation of older archival data, combined with recent observations, will further increase the scientific yield and allow us to track stellar variability over longer timescales.

Citizen science, or the human power for analyzing large datasets

Involving citizen scientists in the analysis of data has multiple benefits, both for the professional scientists as well as for the community, especially, in the light of dwindling numbers of children choosing STEM subjects in the UK and, in particular, in Scotland. Often, we do not know what we can do until we are facing a situation where we can actually do it. For many, the chance never comes. This was not the story of Williamina Fleming and Joanna Mackie, but it could well be the story of youths in underserved communities. Dundee was home to sisters Williamina and Joanna, who, in the late 19th century, emigrated to the US to work as maids. They landed at the house of the Harvard Observatory director, who realized they were too intelligent to be just maids, so he employed them among their women 'computers' to become pioneers in stellar classification.

Interpreting complex variability data when applied to processes that we do not yet understand and for which there are no significant number of examples available yet is still similarly hard as it was a hundred years ago, and because of this, it is still a field where the power of citizen scientists can make a difference. We are starting the Williamina & Joanna School of Variable Stars to bring an opportunity to experience science to young people from Dundee, raising their aspirations and awareness of their own capabilities to do physics and science at a time it can still affect their school decisions, to counteract the STEM subjects' decline observed in Scotland. Imagined as a long-term project similar to "*Light your life*" by Prof. Cornelia Denz [14], we plan to involve local youths in the analysis of North-PHASE data, collaborating with the Mills Observatory in Dundee, which turns 90 years old this year and is the first observatory built with the purpose of public engagement in the UK. The project will launch in January 2026, with the help of staff, PhD and undergraduate students from the University of Dundee. The coming months and year will tell us where the effort of citizen scientists brings us in our quest of *using time to map space*.

References

[1] https://www.esa.int/Science_Exploration/Space_Science/Gaia
[2] https://rubinobservatory.org/
[3] Sicilia-Aguilar, A., Kahar, R., Pelayo-Baldárrago, M., et al. 2024, MNRAS **532**, 2108 "North-PHASE: Studying periodicity, hot spots, accretion stability and early evolution in young stars in the Northern Hemisphere".
[4] https://oajweb.cefca.es/telescopes/jast80
[5] https://oajweb.cefca.es/telescopes/t80cam
[6] Corradi, R. L.M., Highlights of Spanish Astrophysics XII, Proceedings of the XVI Scientific Meeting of the Spanish Astronomical Society held on July 15 - 19, 2024, in Granada, Spain. M. Manteiga, F. González Galindo, A. Labiano Ortega, M. Martínez González, N. Rea, M. Romero Gómez, A. Ulla Miguel, G. Yepes, C. Rodríguez López, A. Gómez García and C. Dafonte (eds.), 2025, "Sustainability in the Spanish observatories"
[7] Knödlseder, J., ADASS XXXII (2022) proceedings, "The carbon footprint of astronomical observatories"; https://arxiv.org/abs/2409.04054
[8] Yanes-Díaz et al. 2018, Proceedings Volume 10704, Observatory Operations: Strategies, Processes, and Systems VII; 1070421 (2018), https://doi.org/10.1117/12.2313208
[9] Yanes-Díaz et al. 2022, Proceedings Volume 12186, Observatory Operations: Strategies, Processes, and Systems IX; 121860Y (2022), https://doi.org/10.1117/12.2626105
[10] Stevens et al. 2019, Nature Astronomy, Volume **4**, p. 843-851, "The imperative to reduce carbon emissions in astronomy", https://arxiv.org/abs/1912.05834
[11] Knödlseder et al. 2024, Nature Astronomy, Volume **8**, p. 1478-1486, "Scenarios of future annual carbon footprints of astronomical research infrastructures", https://arxiv.org/abs/2409.04054
[12] Campbell-White, J, Sicilia-Aguilar, A., et al. 2021, MNRAS **507**, 3331 "The STAR-MELT Python package for emission-line analysis of YSO"
[13] https://github.com/justyncw/STAR_MELT
[14] https://www.uni-muenster.de/Cells-in-Motion/newsviews/interviews/denz.html

Dr **Aurora Sicilia-Aguilar** is a Reader in Physics/Astrophysics at the University of Dundee and the Theme Leader for Astronomy and Space Physics for the Scottish Universities Physics Alliance. Her career developed in the USA, Germany, Spain and the UK. She is an expert on observational star formation, with a particular emphasis on time-resolved data. She is also the PI of the North-PHASE Legacy Survey, an international collaboration currently running at the Javalambre Observatory, Spain.

Dr **Paula Stella De Viveiros Teixeira** is a Lecturer in Physics at the University of Dundee who has cultivated a career working across Portugal, the USA, Germany, Austria, and the UK. While her primary background is in astrophysics and observational star formation, she has transitioned her focus towards environmental science and renewable energy. Currently a member of Astronomers for Planet Earth, her research supports sustainable energy systems by assessing climate impacts and hydro-climatic risks.