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Contents

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Hipparchos is the official newsletter of the Hellenic Astronomical Society. It publishes review papers, news and comments on topics of interest to astronomers, including matters concerning members of the Hellenic Astronomical Society.

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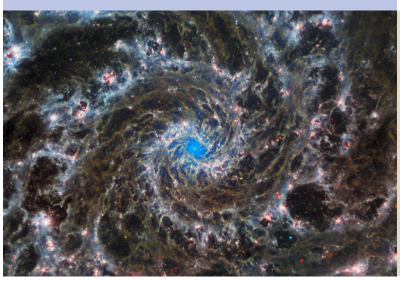

Cover Image: Webb Inspects the Heart of the Phantom Galaxy
The image of the cover page from the NASA/ESA/CSA James Webb Space Telescope shows the heart of M74, otherwise known as the Phantom Galaxy. Webb's sharp vision has revealed delicate filaments of gas and dust in the grandiose spiral arms which wind outwards from the centre of this image. A lack of gas in the nuclear region also provides an unobscured view of the nuclear star cluster at the galaxy's centre. M74 is a particular class of spiral galaxyknown as a 'grand design spiral', meaning that its spiral arms are prominent and well-defined, unlike the patchy and ragged structure seen in some spiral galaxies.

Message from the President

This issue of Hipparchos, the last I have the honor to introduce as the President of our Society, follows the long-standing tradition of including high-quality reviews in select research topics where our community is very active.

Vasilis Archontis (Univ. of Ioannina), who is currently leading a large European collaboration funded by an ERC Synergy grant, is presenting an article about the latest results and open issues related to the physical mechanisms shaping the behavior of our nearest star, the Sun. Paul Kalas (Univ. of California, Berkeley) , who has over 20 years of fundamental contributions to the discoveries of exoplanets and the properties of the circumstellar disks within which they form using mainly space telescopes, is discussing the latest results and breakthroughs in this exciting field thanks to the unprecedent performance of the James Webb Space Telescope. Finally, Ioannis Liodakis (NASA & FORTH), who is starting his career as a permanent researcher in Greece thanks to an ERC starting grant he has received, is helping us peer into the vicinity of the supermassive black holes explaining how we can learn more about their unique characteristics analyzing the polarization of their emission not only in the optical by also in the X-rays.

I would like to thank all authors for taking the time to prepare their articles at a level which is easily accessible even for the non-experts, while maintaining a scientific rigor.

This year is also a year during which the Governing Council of the Society will be renewed. On Friday June 28, 2024 - the day of the General Assembly of the Society – the members of our Society will elect the new President, Council and Auditors for the 2024-2026 terms. As the outgoing President, I would like to thank all members of the Council for their hard work, as well as offering their time and energy to make the goals of the Society a reality. It was a pleasure interacting with each and every one of them, often calling them on the cell phone during odd hours, always in a very friendly and creative atmosphere. In particular I would like to thank Prof. Gourgouliatos and Prof. Tassis, who have completed their two terms as members of the Council and are not candidates again.

I would also like to wish all the best to the candidates for the new Council as well as Prof. Hatzidimitriou, who is the only candidate for the position of the President and thus our expected lead our Society starting this summer. Improving the future of Greek astronomy is a collective effort, which requires both persistence and patience by all of us. In 2024 the Society entered its fourth decade of its life and keeping the communication channels open among the astronomy groups in various institutes in Greece is critical, while inspiring our students and helping the new generation of astronomers to have better conditions for their research are among the implicit duties of the more senior ones. I am certain that our new Council will be very successfully in all those areas.

As a last reminder, this September the Society is organizing its 5th Summer School focused on “Magnetohydrodynamics in Astrophysics” in the beautiful city of Ioannina. Thanks to the efforts of the colleagues from the University of Ioannina and their program which has already been in place, I have no doubt that this will be a formative experience to everyone who will be attending it.

Vassilis Charmandaris
President of Hel.A.S.

1993-2023

Our Sun: a laboratory for astrophysical studies

by **Vasilis Archontis**

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Abstract

The physical processes, which drive the solar magnetic activity, play an important role in our understanding of the Sun–Earth connection and the nature of powerful events, such as flares, jets and eruptions, which can occur in various astrophysical environments. In this short review, we discuss how magnetic fields emerge from the solar interior to the solar surface, to build up active regions, which trigger the afore-mentioned phenomena during their evolution. Some of the open key questions related to this research topic are presented at the end of the article.

Magnetic flux emergence and active regions

It is generally accepted that dynamo-generated magnetic fields are transported from the solar interior to the visible surface of the Sun (photosphere) by magnetic buoyancy (Parker, 1955). Convective motions (updrafts and downdrafts) have an impact on the buoyant emerging fields, which may develop a serpentine-like configuration over a wide range of spatial scales. Thus, on small scales (e.g. 1–2 Mm), the emerging field appears to the photosphere in the form of small magnetic bipoles. On large scales (e.g. 100 Mm), the interplay between convection and the dynamic interaction of the small emerging bipoles (cancellation, coalescence, etc.) can lead to the formation of sunspots and Active Regions (ARs) (Zwaan 1985) (figure 1).

Three dimensional numerical simulations, solving the resistive full magnetohydrodynamic equations (MHD), have revealed the turbulent nature of the internal structure of ARs (top-left panel, figure 2). It consists of short and longer twisted filaments of strong currents, which evolve dynamically over time and space, leading to heating of the plasma via turbulent reconnection of sheared magnetic fieldlines. The simulations show also the connectivity of the magnetic field, which forms the expanding coronal loops in the higher solar atmosphere. Both, the coronal loops and the heating of the plasma is common observed features in ARs (top-right panel, figure 2).

Another characteristic of ARs, which usually lead to eruptions of magnetized plasma, is their S-shape morphology (sigmoids, bottom-right panel, figure 2). Statistical studies of observations show that a considerable amount of sigmoidal ARs erupt, giving onset to Coronal Mass Ejections (CMEs). Numerical simulations show that the S-shape of the field is the result of the formation and complex interaction between many twisted and strong currents inside the AR (bottom-left panel, figure 2).

Eruptions of plasma - CMEs

Solar filaments (called prominences when observed on the limb of the Sun) are magnetized plasma structures that hold cool and dense plasma, suspended over the surface of the Sun. Coronal Mass Ejections (CMEs) are fast expulsions of large filaments from the solar corona, ejecting billions of tons of plasma towards the interplanetary space. When CMEs are directed towards Earth and disturb it's magnetic field, they can cause geomagnetic storms. Various observational studies have reported on the pre-eruptive stage of the eruption, the onset and the propagation of the erupting field towards the interplanetary space (e.g. Vourlidas, A. et al., 2012, Chintzoglou, G. et al., 2015, Patsourakos, S. et al. 2016). It is believed that the core of the erupting field has the form of a sheared arcade or a twisted magnetic flux tube (i.e. magnetic flux rope, MFR) (e.g. Zhang, J. et al. 2012).

Observational studies (e.g. Zhang, Y. et al. 2008) have reported statistical surveys, comprising ARs and CME-source regions, towards understanding the relationship between surface magnetic field variation and CME initiation. Theory and numerical simulations (figure 3) show that the core of the eruptive plasma can be formed by reconnection of sheared fieldlines above strong polarity inversion lines (e.g. van Ballegooijen A. & Martens PCH., (1989), Magara T & Longcope DW. (2001), Archontis V. & Török T. (2008), Fan, Y. (2009))

The use of pseudo-synthetic images can reveal more features of the erupting field. For instance, Figure 4 (left panel) shows the plasma emission during a simulated eruption using two AIA (Atmospheric Imaging Assembly) extreme ultraviolet channels at 170 and 304 A. In fact, this image shows the dense erupting plasma over a range of temperatures. The erupting core consists of dense and cool plasma and it might account for an erupting filament. The cavity is located above the erupting core and it is less dense. The edge of the eruptions outlines the overlying field that has been expanded into the higher corona. Underneath the erupting field, the plasma is heated to very high temperatures (up to $5x10^6$ Kelvin) and it might account for a solar flare, which is formed at a current sheet above the PIL, where the sheared fieldlines reconnect. Overall, there is a very good comparison between the results of the simulations and high-resolution observations.

An important question is whether these simulated eruptions can actually evolve and form CMEs. The right panel in Figure 4 shows the extrapolated size of the erupting volume of the simulation at 0.6 solar radius above the solar surface. The black box has the physical size of the simulation box. It is clear that although the eruptions originate from a small-scale region, they grow in size, and it is not unlikely that they will evolve into considerably larger-scale events. We should note that the above method is a first-order approximation regarding the spatial evolution of the eruption, assuming that the erupting field will continue to rise and expand

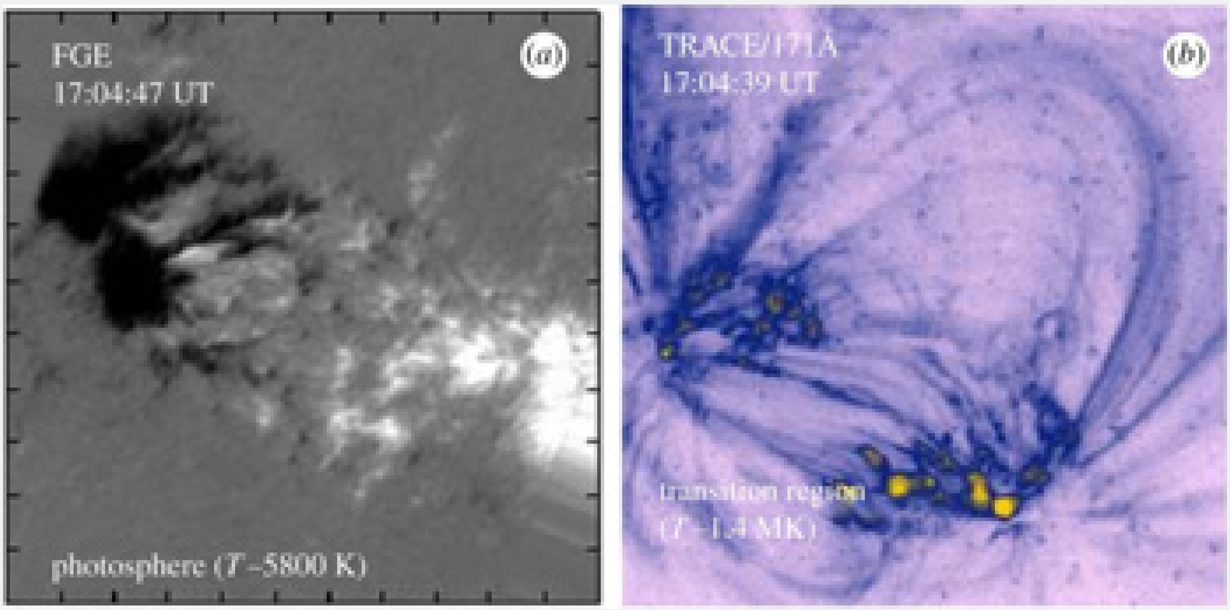

Figure 1: (a) Formation of an AR, following magnetic flux emergence. Vertical component of photospheric magnetic field (white is positive and black is negative magnetic polarity). (b) View of (a) in EUV 171 Å (transition region), showing how loops of magnetic fieldlines join the opposite polarity fields in the AR. Adapted from Schmieder, B. et al. 2014.

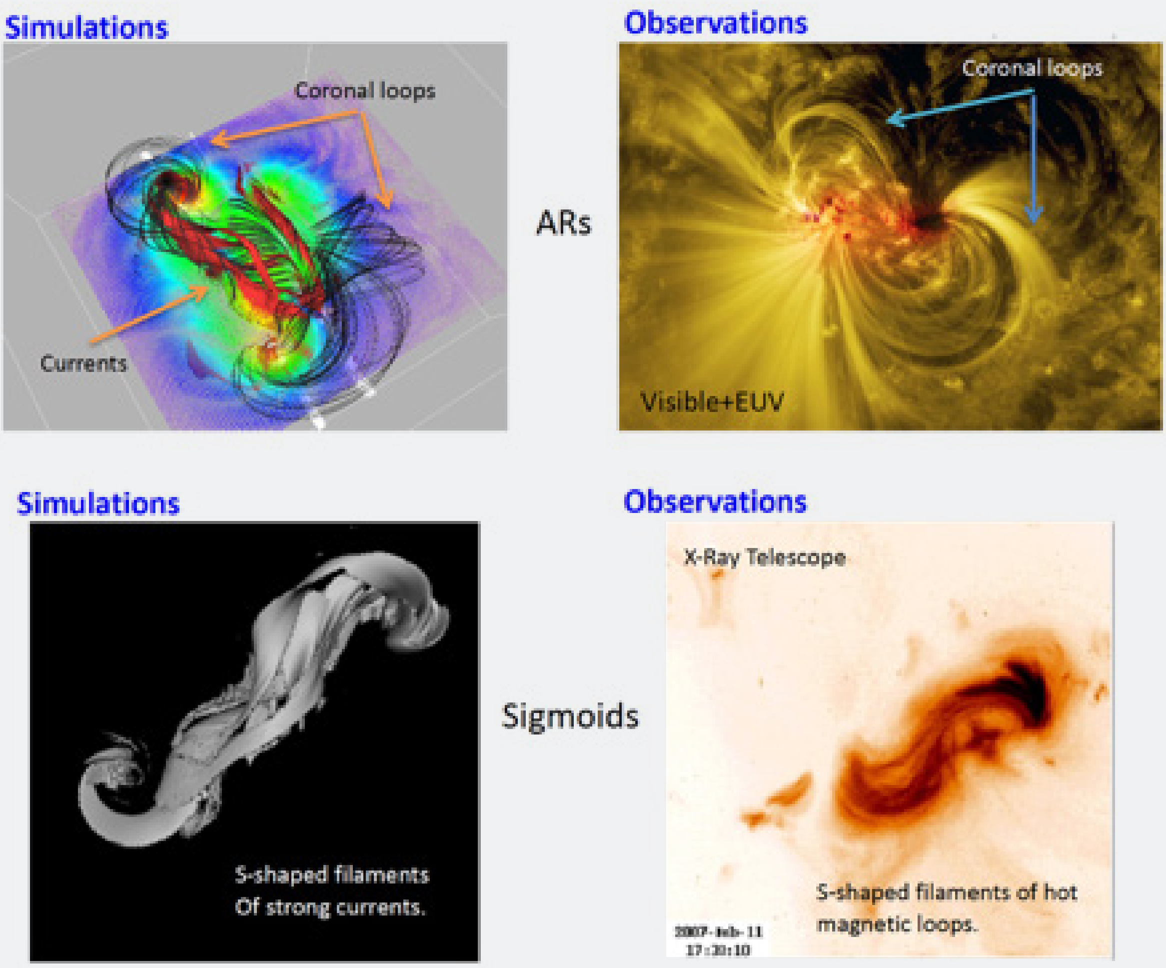

Figure 2: Comparison between simulations (Archontis and Hood 2008, top-left and Archontis et al. 2009, bottom-left) and observations (AR12665 2017 NASA/SDO, top-right and McKenzie and Canfield 2008, bottom-right) of ARs (top row) and sigmoids (bottom row).

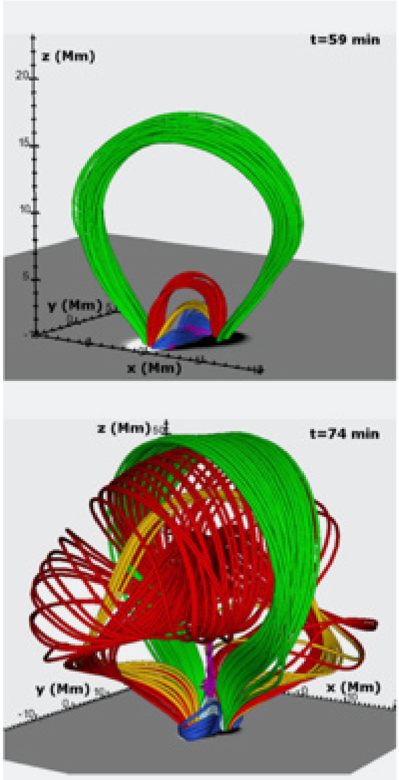

Figure 3: 3D numerical MHD simulations of solar eruptions by Syntelis et al. 2017. The horizontal slice shows the solar photosphere, where a small AR is formed by magnetic flux emergence. White and black show the positive and negative polarity of the emerging region. Top panel: the low-lying magnetic fieldlines experience shearing and reconnection at the PIL between the positive and negative polarity, transforming a sheared arcade into a highly twisted flux tube (MFR). Bottom panel: the MFR (mixture of red and yellow lines around its core) erupt with high speeds (200 -500 km/sec) towards the outer solar atmosphere.

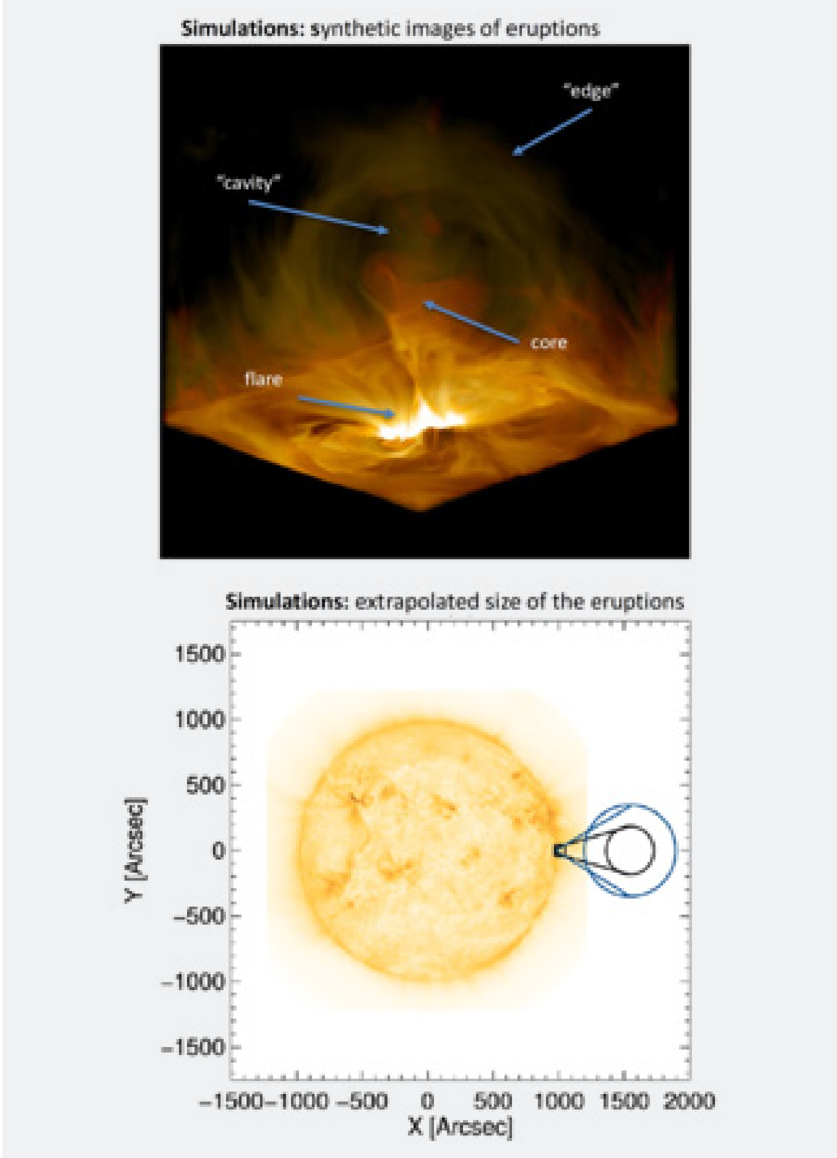

Figure 4: Pseudo-synthetic images of a CME-like eruption using the simulations by Syntelis, P. et al. 2017 (left panel). Geometrical extrapolation of the simulated eruption showing that it can gradually get the size of a small CME.

even after it leaves the numerical domain.

The maximum value of the magnetic energy in the simulated eruptions is 1 × 10^{28} erg and the kinetic energy varies in the range 3x10^{26} - 1.5x10^{27} erg. Based on the size of the numerical box and the aforementioned values of energies, the eruptions in such simulations could describe the formation and ejection of small-scale CME-like events. Most CMEs have typical values of kinetic energies around 10^{28} - 10^{30} erg (Vourlidas, A. et al. 2010).

Solar jets

A common phenomenon in the Sun is the fast ejection of collimated plasma outflow at different locations in the solar atmosphere and at different temperatures (solar jets). Observations of X-ray jets in the solar corona (Figure 5) show that these jets have some common features. For instance: a) there is a hot column of plasma ejected in the corona, b) the jet adopts an inverted Y-shape configuration, c) there is a flaring bright point (BP) off to the side of the jet and d) the vertical jet spire migrates away from the BP.

Most of the observational features of the X-Ray jets have been reproduced in various numerical simulations, which studied the emergence of a twisted flux tube and it's reconnection with a pre-existing magnetic field in the corona. However, the observational study of jets by Sterling et al. 2015, revealed that a large number of solar jets is triggered by the eruptions of small scale (mini) filaments. These jets were initially called as 'blowout' jets, because during their ejection, they blow out the surrounding magnetic field. This new class of jets has a distinct number of features: a) the spire of the jet is wider, b) the ejected plasma is multi-thermal, d) the jet is basically triggered by the eruption of cool and dense low atmospheric plasma, which may account for a mini-filament. Simulations of magnetic flux emergence and reconnection with the pre-existing coronal magnetic field (e.g. Archontis, V. & Hood, A. 2013, Moreno-Insertis, F. and Kalsgaard, K. 2013) have reproduced all the key features of the 'blowout' jets

Figure 5: Observations showing an X-Ray jet at different wavelengths (Patsourakos, S. et al. 2008).

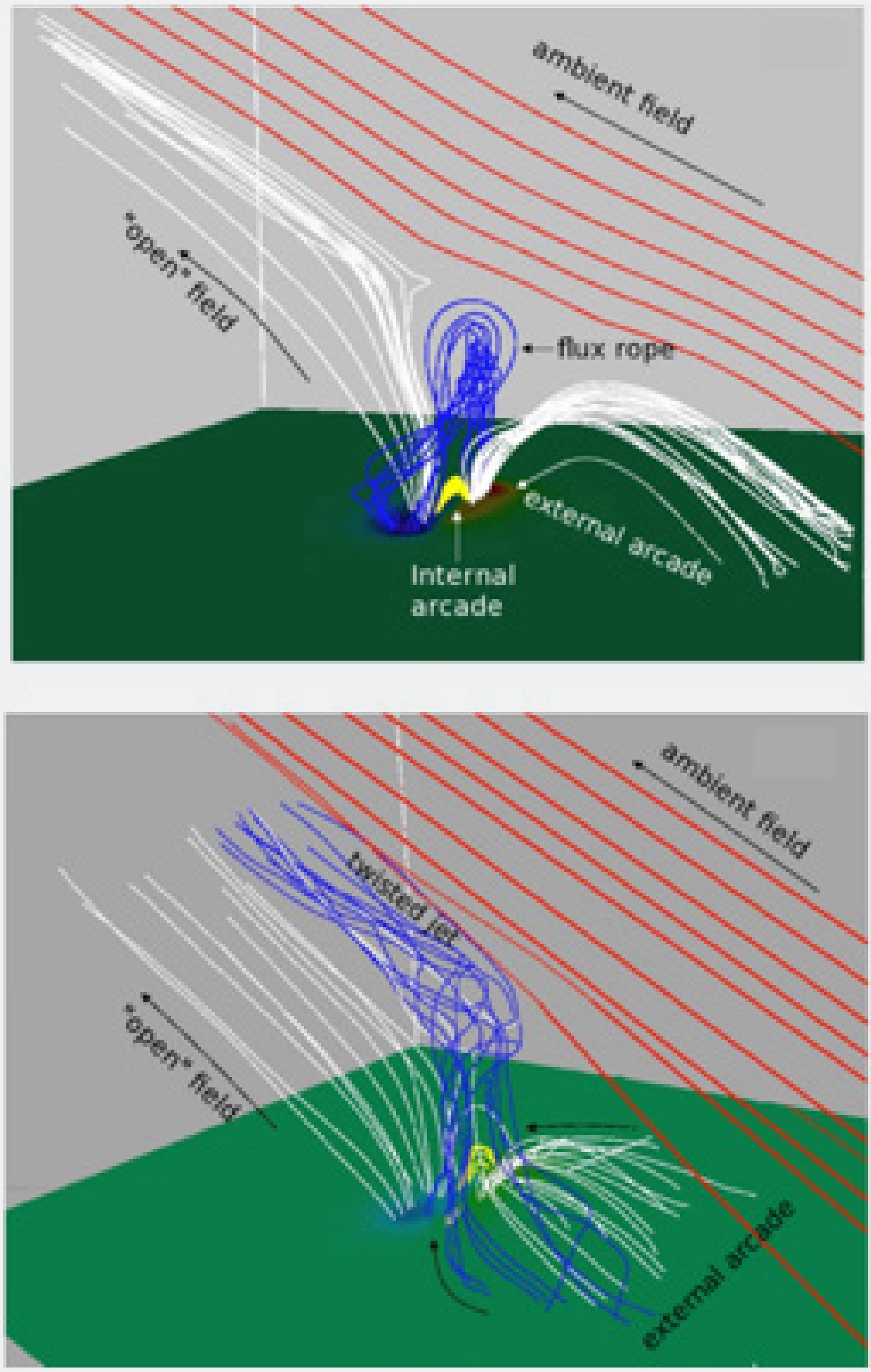

Figure 6:
Simulations of 'blowout' jets in the Sun (Archontis, V. & Hood, A. 2013). Top panel: the initial eruption of a MFR (blue fieldlines). Bottom panel: the ejection of the MFR along the reconnected ambient field, forming a twisted blowout jet.

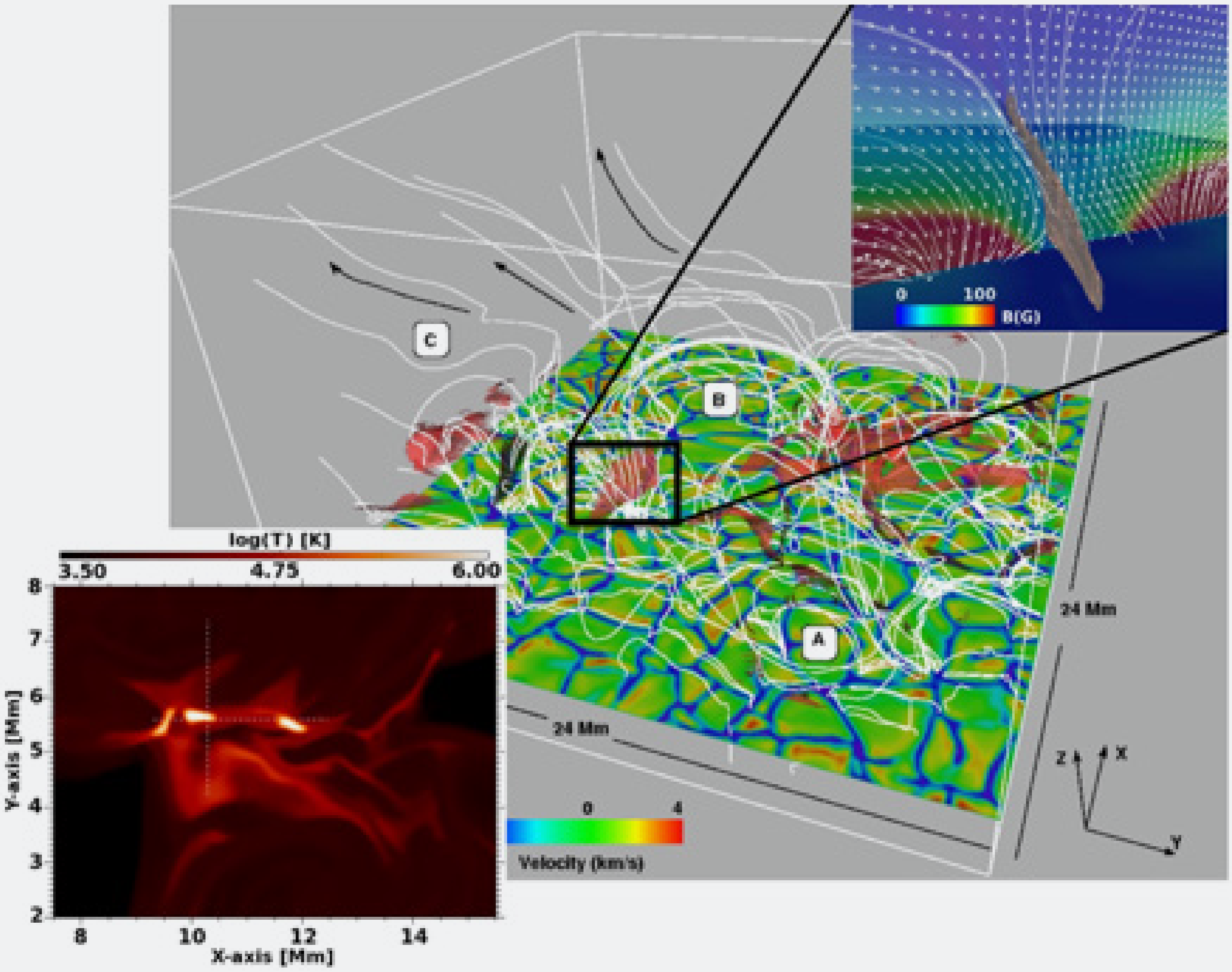

Figure 7: Simulations of radiative MHD flux emergence on small scales (Archontis, V. & Hansteen, V. 2014). Central panel: the horizontal slice shows granular convection, which drives emergence of multiple small-scale magnetic loops, which interact with each other, leading to formation of current sheets. The labels A,B,C show small magnetic loops, larger magnetic loops and reconnected fieldlines respectively. Top-right panel: Close up of a current sheet between emerging loops. Bottom-left panel: Intermittent heating (microflares/nanoflares) inside a fragmented current sheet.

(Figure 6). The filament is formed in the same way as it has been described in the previous section. This filament has the shape of a twisted flux tube (MFR) and it carries cool and dense plasma from the low solar atmosphere. The cool and dense plasma is located at the dips of the twisted fieldlines of the MFR and it is transferred upwards during the eruption of the MFR. The reconnection between the emerging and the pre-existing magnetic field works as a 'breakout' reconnection and it opens the way above the erupting MFR. The reconnection at the flare current sheet below the MFR together with the breakout reconnection trigger the fast eruption of the MFR. The ejected material of the jet is cool (from the MFR) and hot (from the two reconnection sites). The channel of the jet is wider because it encompasses the MFR, which is ejected along the spire of the jet. These results reveal the connection between jets and large scale eruptions, such as CMEs, since both can be triggered by eruptions. An extended review on solar coronal jets has been given by e.g. Raouafi, N.E at al. 2016.

Heating of the solar atmosphere

The heating of the solar atmosphere is a key open topic of research in solar physics. One of the suggested heating mechanisms is the ubiquitous occurrence of flares. Observations (e.g., Lin et al. 1984) have revealed the existence of numerous microflares (transient brightenings with energy O(10^{27}) erg and size smaller than the standard flares on the Sun. The areas around microflares are often bright in X-rays, which implies plasma heating (e.g., Porter et al. 1987). Thus, microflares have been considered as possible sources for heating the solar corona, subject to their occurrence rate and energy release. On theoretical grounds, Parker (1988) suggested that the active X-ray corona consists of numerous nanoflares (O(10^{24}) erg, with the largest nanoflares approaching 10^{26}–10^{27} erg and that microflares could be made up of several nanoflares.
Radiative MHD simulations have shown that small flares are formed naturally by patchy reconnection, in fragmented current sheets, between interacting magnetic bipoles (Figure 7). The fragmentation of currents explains naturally the ubiquitous intermittent heating and filamentary nature of the solar corona (Vlahos, L. and Isliker, H. 2023).

Simulations (e.g. Archontis, V. and Hansteen, V. 2014) have revealed that the frequent onset and co-operative action of small flares dump enough energy in the solar atmosphere, sufficient to accelerate and heat the plasma in the active corona.

The flares produced in these numerical simulations appear at random intervals, with an average lifetime of 30 sec – 30 min. They occur at various atmospheric heights (chromosphere–corona) and they are capable of heating the plasma to ≈1–6 MK. Some of these flares are individual energy emissions of O(10^{27}) erg and they might account for microflares. However, many of the events with noticeable total energy release is the result of the superposition of small flares, each involving 10^{25}–10^{26} erg, which is the nano/microflare energy regime. For the small flares that occur in the corona, the simulations have showed that the average energy flux was at least O(10^6) erg s^{-1} cm^{-2}. This estimate, together with the high occurrence rate of flares in the same area, indicated that nano/microflares can provide a non-negligible contribution of heating in emerging flux regions and in the active X-ray corona. Moreover, the simulations have showed that the fast upward propagation of plasma, which originates mainly from the flare regimes, carried a vast amount of Poynting flux into the corona (in the range 1–60 kW m^{-2}), part of which could contribute to the mass loading and driving of the solar wind. The mechanism presented in these numerical experiments may constitute a generic process, which powers eruptive flaring activity of magnetic fields in astrophysical and laboratory plasmas.

Discussion

We have presented a short review on some of the most important phenomena in the Sun.

The 'Whole Sun' project (ERC Synergy Grant, 2021-2026, University of Ioannina, University of Saclay/Paris, University of Oslo, Max-Planck institute) tackles the afore-mentioned research topics by means of theory, ground-based and space observations and high-performance computing. In addition, the 'Whole Sun' project investigates the nature of open problems in solar physics and astrophysics, such as:

1) The coupling between the large-scale dynamo generated field and it's emergence to the solar surface and above.
2) The impact of kinetic effects on radiative MHD solar models, including the particle acceleration in fragmented current sheets.
3) The thermodynamic coupling between the solar interior and the outer solar atmosphere and the nature of coronal heating.
4) The incorporation of solar wind into the solar models and it's implications to the study of space weather.
5) The study of emergence, jets, flares and eruptions in other stars.
6) The build-up of a global code, from the solar interior to the solar wind, which could run on exa-scale supercomputers.

Acknowledgments

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JWST's Surprising Views of Circumstellar Disks

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Introduction

The infrared has always served as an essential astronomer's tool for characterizing the circumstellar dust disks where planetary systems are born and evolve. Dust grains are heated by UV and optical light from the central star and then the reradiation of this heat is detectable with our instruments. When this thermal emission is unresolved its infrared peak in the spectral energy distribution can be translated to a blackbody temperature and hence the dust grain's radial distance from the star. We therefore learned that very young *protostars* in *distant* (>120 pc) star-forming regions were surrounded by the dust disks that theory required for the formation of planetary systems.

Forty years ago the IRAS mission yielded perhaps the greatest infrared surprise of the 20th century: *older*, *nearby* (<20 pc) main sequence stars such as Vega, Fomalhaut, and beta Pictoris also had excess infrared emission from circumstellar dust (Aumann et al. 1984). Because the dust lifetime is orders of magnitude shorter than the host star age, we inferred the existence of colliding planetesimals that could replenish the observed dust. By employing coronagraphy to suppress the light from these very bright stars, a faint nebulosity of dust-scattered light was revealed around beta Pictoris in the form of an edge-on disk (Smith & Terrile 1984). The second surprise was that the morphology of the disk was asymmetric (Kalas & Jewitt 1995, Mouillet et al. 1997) and this began the direct-imaging search for extrasolar planets within beta Pic and other debris disk systems that could dynamically distort the structure.

It is no wonder then that young stars with dusty debris disks and extrasolar planets would be primary targets for JWST in six Guaranteed Time Observing programs and one Early Release Science program. These experiments would aim to use NIRCam and MIRI to detect new disk structures, search for water and CO ices, and directly detect and characterize extrasolar planets. Many interesting results from these very first observations have been published, but what are the surprises that no one anticipated? The topic of surprises will be the focus of this article, and no doubt there will be many more to come. First I will offer a quick primer on the observing strategies that are specific to this type of science, and then I will review three papers that offered some startling findings.

Tools and strategies to achieve high-contrast with JWST

Detecting circumstellar material reflecting starlight or emitting at thermal wavelengths requires canceling starlight. ALMA is a great tool because emission from a hot star is intrinsically very low as radiation drops with the Rayleigh-Jeans tail at sub-mm and mm wavelengths. Therefore one can detect and study the spatial distribution of mm-sized dust grains that have been warmed by the star.

However, at shorter wavelengths, the starlight can be many orders of magnitude brighter than circumstellar dust or planets. In addition to coronagraphy to artificially eclipse the star, one trick is to image in polarized light in two channels simultaneously since stellar photons are unpolarized whereas light scattered by circumstellar dust grains become polarized (e.g., Perrin et al. 2015). By taking the difference of the simultaneous images, the starlight is subtracted while the polarized light remains for further analysis. This method has been successful using advanced ground-based adaptive optics systems to detect and characterize faint disks at Gemini Observatory (e.g. Esposito et al. 2020) and the VLT (e.g. Avenhaus et al. 2018).

JWST is neither a sub-mm observatory nor does it feature dual-channel polarimetry. Instead, starlight suppression is attainable by virtue of (1) its stable, diffraction-limited PSF, (2) the ability to roll the telescope around the optical axis, a form of rotational dithering (3) the availability of coronagraphic elements in the cameras, and (4) by scheduling the observations of stars without circumstellar material merely to have a near-simultaneous image of the telescope's PSF which can be subtracted from the science target's PSF. All four of these principles are also used for high-contrast imaging with the Hubble Space Telescope and ground-based instruments with adaptive optics.

Thus most papers on high-contrast imaging will refer to three key phrases: (1) *angular differential imaging* (ADI), (2) *reference differential imaging* (RDI), and (3) the *inner working angle* (IWA). With ADI, the field is imaged two or more times but never at the same position angle in the detector frame. The stellar PSF is centered on the optical axis, but the astrophysical field rotates around this axis from exposure to exposure. By differencing these images the central PSF is subtracted while the astrophysical field has a pattern of positive-negative pairs of sources. These difference images can then be rotated so that all the positive features are co-registered and then combined. RDI simply requires the observation of a PSF reference star to subtracted the science target PSF without the need for field rotation. However, because there are limitations to the angle that a telescope can be rotated for ADI, and an extended object will self-subtract when the angle is too small, many observations are designed to use *both* RDI and ADI. This is particularly true for JWST because the telescope rotation is limited to ~10° for a given epoch of observation.

After all the processing for PSF subtraction is completed, the IWA refers to the closest radius from a star that is sensi-

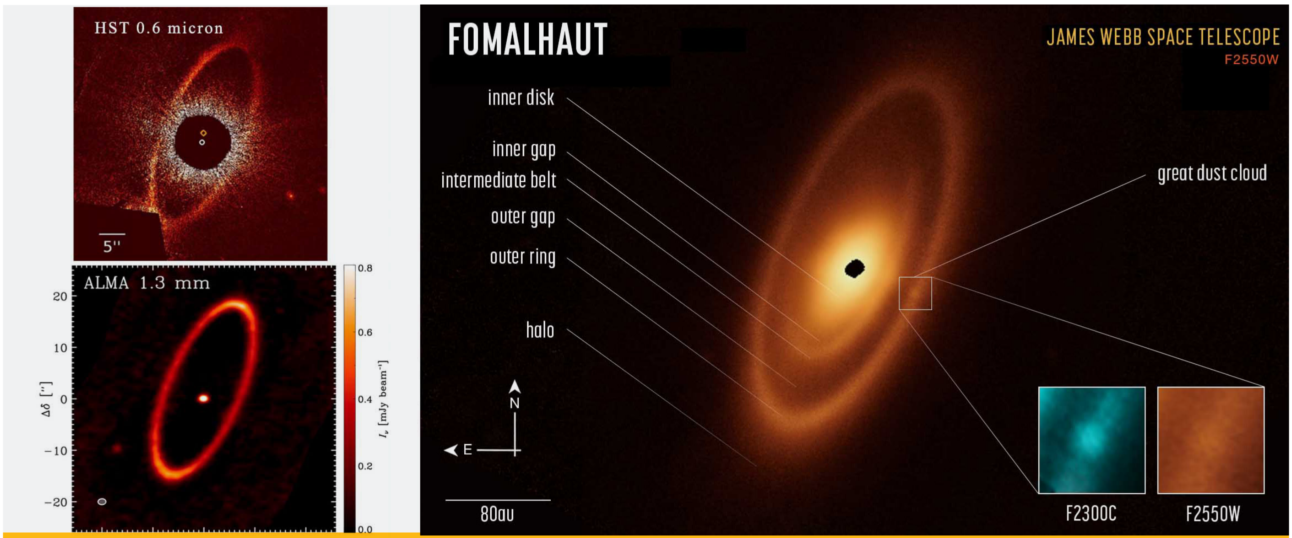

Figure 1: Fomalhaut's dusty debris belts mapped in the optical, mm, and at 25 μm with JWST. **LEFT:** The prior images revealed a narrow dust belt at 140 au radius. The HST scattered light image (Kalas et al. 2013) and ALMA thermal emission map (MacGregor et al. 2017) show that the geometric center of the belt is offset from the location of the star. This stellocentric offset and the sharpness of the belt edge are consistent with dynamical sweeping by an eccentric planet. **RIGHT:** The first JWST/ MIRI observations at 25.5 μm revealed the existence of a second narrow belt called the "intermediate belt" (Gaspar et al. 2023), which was not detected in the prior images.

tive to astrophysical information. Typically this is limited by the angular size of the coronagraphic element used for the observation. In JWST papers one often sees a dashed circle, which marks the radius where a coronagraphic occulting spot has 50% transmission. However, the IWA may be larger than this radius when significant PSF subtraction residuals exist at larger radii.

Fomalhaut

The JWST/MIRI images of Fomalhaut at 23 and 25.5 μm (Gaspar et al. 2023) stunned the debris disk community with the discovery of a distinct, intermediate dust belt at ~90 au that had not been previously seen in the optical with HST (Kalas et al. 2005, 2013), at 70 μm with Herschel (Acke et al. 2012), or with ALMA at 1.3 mm (MacGregor et al. 2017). This 440-Myr-old A3V star at 7.7 pc, had been previously studied by every major observatory and was known to have both cold dust at ~140 au, and a warmer inner disk component detected with Spitzer at 24 μm that appeared "smoothly distributed" rather than ring-like (Stapelfeldt et al. 2004). The geometric center of the 140-au dust belt was found to be situated 15 au away from the star (Kalas et al. 2005), indicating that it is intrinsically eccentric (e ~ 0.1), which is supported by the theory of a secular perturbation by an eccentric planet (Wyatt et al. 1999). Multi-epoch imaging with HST revealed the existence of an optical point source called Fomalhaut b (Kalas et al. 2008) which was thought to be the planet predicted by secular theory. Since it was detected only in the optical, Fomalhaut b could represent light reflected from a circumplanetary dust ring. The alternative explanation is that it represents an unbound dust cloud resulting from the collisional destruction of two planetesimals (Gaspar & Rieke 2020), implying that the hypothesized eccentric *planet-mass* perturber of the 140-au belt has not been discovered yet.

Given the scientific interest in directly imaging the hypothesized planet and making progress in understanding the co-evolution of planets and disks, Fomalhaut was targeted for both MIRI and sensitive NIRCam observations which could probe near the Saturn masses that were unattainable from the ground. The NIRCam coronagraphic observations with the F356W and F444W filters achieved IWA~0.85" (6.5 au) but neither Fomalhaut b nor any other planet was definitively detected (Ygouf et al. 2024). One red source will be tested for common proper motion in a follow-up JWST observation. From ~0.4" (3.1 au) and outward, the observations would have detected a planet 0.6 Jupiter masses or greater, thus leaving open the possibility that Saturn-mass gas giants reside in the system.

The more significant and surprising result came from the MIRI observations with the discovery at 83 –104 au of a misaligned intermediate dust belt situated between a warm inner disk and the cold outer belt (Fig. 1). Measurements made by Gaspar et al. (2023) indicate that the intermediate belt is tilted by 7.4° – 22.9° relative to the 140-au outer belt and has a much larger eccentricity in the range 0.27 – 0.31. Another major finding was a clump of emission within the 140-au belt that Fig. 1 labels as the "Great Dust Cloud" generated by a recent planetesimal collision. However, by studying archival Keck and ALMA data, Kennedy et al. (2023) showed that this source is a background galaxy which fortuitously landed behind Fomalhaut's dust belt at the epoch of JWST's observation.

To summarize, JWST's discovery of a misaligned intermediate dust belt motivates substantial new research efforts for interpreting the dynamics of the system. The two gaps on either side of the intermediate dust belt could be cleared by planet-mass objects, but what would their orbital properties have to be in order to make the intermediate belt tilted and more eccentric relative to the outer belt? Are those orbital configurations stable or are we catching Fomalhaut's planetary system in a brief chaotic period resembling the solar system's late heavy bombardment?

My approach has been to question the intermediate belt's morphology that is inferred from Fig. 1. The belt is not clearly seen between PA = 0° and 120°. This missing information allows for the possibility that it could actually have a spiral shape. The spiral could be exactly coplanar with the outer belt, but if a portion of it is fit as an ellipse, that el-

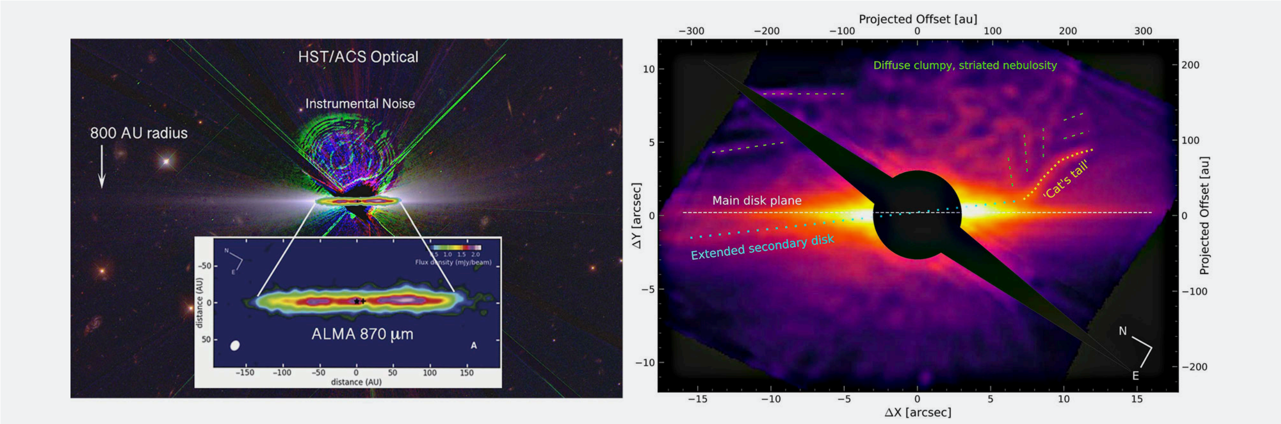

Figure 2: LEFT: In optical scattered light, deep imaging with HST's Advanced Camera for Surveys shows that beta Pic's debris disk extends beyond 800 au radius, it is viewed edge-on, and has asymmetries such as the NE side (left) extending to a greater distance than the SW side (right). The inset shows the ALMA sub-mm map and a clump of emission on the SW side that may signify a fresh dust cloud produced by the catastrophic collision of two planetesimals (Dent et al. 2014). **RIGHT:** The JWST/MIRI 23 µm observation that shows filamentary features in the upper right quadrant of this image and a prominent "cat's tail" structure that are not detected at other wavelengths such as in the left panel (Rebollido et al. 2024). The dashed lines are superimposed on features that are astrophysical and not instrumental.

lipse will appear to be more eccentric and tilted relative to the outer belt. To test this idea, we have new HST observations planned that have been designed to be sensitive to dust scattered light from the intermediate dust belt. Whatever the case turns out to be, it is already clear that the surprising JWST/MIRI results will catalyze new thinking in how dusty debris belts co-evolve with a planetary system.

Beta Pictoris

More than an order of magnitude younger (~24 Myr) than Fomalhaut and more than twice as distant (19.3 pc), the A5V star beta Pictoris is perhaps the single most-studied planetary system of all. Smith and Terrile (1984) first discovered beta Pic's edge-on dust disk in seeing-limited, optical scattered light and noted that since the starlight showed no evidence for extinction, the dust must be depleted near the star, possibly by the dynamical action of planets. The disk-planet interaction hypothesis received further support when a vertical warp was discovered in the disk within 50 au radius suggesting a secular perturbation by a planet inclined relative to the main disk midplane (Mouillet et al. 1997). Additionally, time-domain spectroscopy revealed variable features that were attributed to infalling comets perturbed by a hypothetical planet (Lagrange et al. 1987). The ~10 Jupiter mass beta Pic b was eventually discovered via direct imaging with semi-major axis a ~ 10 au (Lagrange et al. 2009). A second gas giant planet, beta Pic c, with a ~ 3 au was recently revealed via radial velocity observations (Lagrange et al. 2019). Other intriguing observations with ALMA revealed a CO clump along the southwest side of the disk at ~85 au that is consistent with the recent collisional destruction of a planetesimal (Dent et al. 2014). The science drivers of the first JWST NIRCam and MIRI observations of beta Pic were to image the disk at multiple wavelengths to detect any absorption features due to water and CO ice, as well as to search for thermal emission from sub-Jupiter mass planets (Rebollido et al. 2024). Yet the main findings were completely unexpected: The 15.5 µm and 23.0 µm MIRI observations revealed that the region west of the southwest midplane contains a striated nebulosity, with the most prominent feature dubbed the "cat's tail" (Fig. 2). The tail seemingly emerges off the southwest midplane at 125 au radius and a 45˚ angle, reaching as far as 265 au radius. These features are not instrumental artifacts as they are detected at both wavelengths and at the two different telescope roll angles. As with Fomalhaut's intermediate belt, it is surprising that sensitive imaging at other wavelengths, including JWST's own NIRCam observations from 1.8 µm to 4.4 µm, did *not* detect these features. Additionally, the cat's tail has a uniformly blue color between the two MIRI filters.

Rebollido et al. (2024) suggest that recent planetesimal collisions southwest of the star, which can account for the previously known CO clump, also generate outflowing tails of dust grains due to radiation pressure. The collision sites are within the secondary disk which is inclined by ~5˚ relative to the primary disk, and thereby allow tails to extend above the primary disk midplane in the sky projection. The blue color in the mid-infrared and the lack of optical/NIR scattered light are consistent with models of porous organic refractory grains. The striated features detected west of the disk can be explained if several older collision events produced tails in the past which are still visible as faint remnants near the disk. However, a careful inspection of the 23 µm image in Fig. 2 should trigger some puzzlement. The cat's tail appears to have a roughly uniform brightness with radius, but if it represents dust scattered-light its brightness should rapidly diminish as distance squared from the star, or if it represents thermal emission, it should be hotter (bluer) closer to the star. Future work is needed since the current model does not replicate the brightness distribution observed in the cat's tail.

Edge-on protoplanetary disks

Very young (1–3 Myr), gas-rich protoplanetary disks that are viewed edge-on permit the study of their vertical structure. Their midplanes are optically thick and hence block the direct views of starlight; no coronagraphy is needed! Light is scattered towards the observer from the top and bottom layers of the disk where the dust volume density has decreased sufficiently for it to become optically thin at a given wavelength. The extinction as a function of wavelength depends on the grain properties such as the size distribution. This enables the following experiment: By imaging an edge-on disk at many wavelengths, one can infer the grain size distribution by measuring the chromaticity of the mid-plane's vertical width. These findings can be connected to the physics of the disk because grain settling towards the midplane will depend on the strength of their entrainment in disk gas. Small grains are most strongly entrained, but if the disk gas is turbulent, it can hinder the settling of smaller grains.

Before JWST became available, the feasibility of this experiment was extremely limited. Figure 3 shows one of the largest Myr-old disks in Taurus, Tau 042021 (2MASS J04202144+2813491), with dust extending to ~400 au radius and CO gas reaching ~1000 au (Duchêne et al. 2024). The ALMA mm data reveal the thermal emission from mm-sized grains, and these are concentrated within the disk midplane as a result of extremely efficient settling. The sub-micron grains are probed at optical wavelengths by the HST data showing a biconical morphology, but the color dependence of the dark lane at the midplane is only measurable within a small range of wavelengths. Thus, new JWST observations can deliver the first information on the disk's scattered-light structure at the longer, mid-IR wavelengths that are diagnostic of 10-20 μm grains.

Figure 3 shows that the dark lane's vertical width was found to decrease only modestly with increasing wavelength, consistent with an approximately gray opacity law rather than the steep dependence with wavelength expected for interstellar grains (Duchêne et al. 2024). Thus a simple inspection of these panchromatic images reveals grain growth in the disk surface to at least ~10 μm size. Duchêne et al. (2024) note that dark lanes for other disks studied out to 5 μm become much thinner between the optical and infrared. The result for Tau 042021 is therefore consistent with the existence of turbulent disk gas that prevents the 10 μm grains from settling to the midplane.

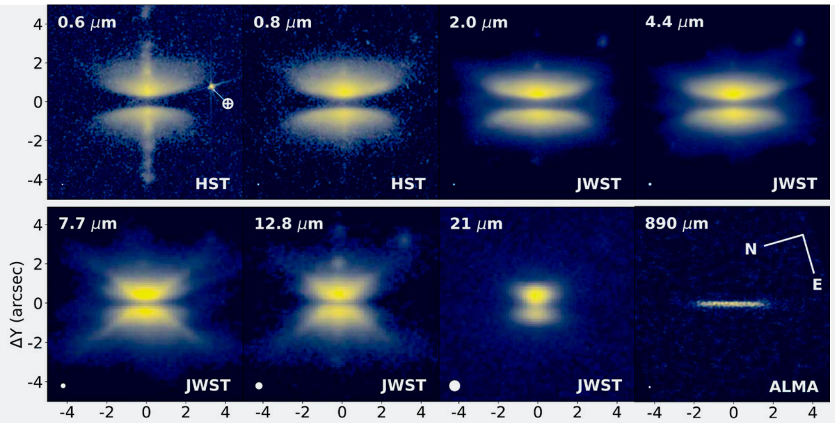

Figure 3: Investigating the panchromatic changes in vertical disk thickness for the protoplanetary disk surrounding Tau 042021 (Duchêne et al. 2024). The dark lane imaged for the first time with JWST NIRCam and MIRI does not become as narrow as expected from 0.6 to 21 μm, suggesting that 10-μm grains are vertically extended above and below the midplane by turbulent disk gas. The greatest surprise is the discovery of a symmetric X feature in the 7.7 μm and 12.8 μm images which has not yet been thoroughly explained theoretically.

The major surprise from this JWST imaging campaign is not the chromaticity of the lane width, but the symmetric X-shaped feature evident in the 7.7 μm and 12.8 μm data (Fig. 3). This has not been seen before in a protoplanetary disk. The X is defined by four linear features extending ~225 au above the disk midplane and angled at ~36˚. If the X were caused by dust-scattered light, it should have appeared in the 4.4 μm data also. The physical nature of the X is now open to further theoretical interpretation. The authors briefly speculate that the X shape arises from H_2 photodissociation or non-thermal emission from < 0.1 μm sized grains entrained in a conical disk wind.

Ongoing and future work

The number of astrophysically surprising JWST results will surely increase in the near future given the many novel programs that have been approved in the first three regular Guest Observer (GO) proposal rounds. A few previously known extrasolar planets have been imaged with JWST so far (Carter et al. 2023, Miles et al. 2023, Ygouf et al. 2024) but there are at least a dozen approved GO programs that will be surveying many more stars like beta Pic and Fomalhaut in order to detect their hypothesized planetary companions. To better understand the nature of beta Pic's cat's tail, GO-5298 (PI Perrin) in Cycle 3 will obtain MIRI medium resolution spectroscopy. The search for Fomalhaut's perturbing planets will also be renewed with a deeper NIRCam imaging campaign in Cycle 3 (GO-5557, PI Janson). Finally, many more edge-on protoplanetary disks will be targeted in a Cycle 2 program (GO-4290, PI Menard) to determine if the X feature is rare or universal, and follow up spectroscopy of Tau 042021 will check for emission line tracers in the NIR and mid-IR.

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Black hole processes revealed through their polarized emission

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Black holes (BH) in the centers of galaxies have puzzled scientists for decades. While we have greatly increased our understanding regarding how matter behaves in the extreme conditions close to a black hole, the physical processes on small scales, particle interactions at high energies, and the behavior of magnetic fields in extreme gravity still elude us. These physical processes manifest themselves in different ways, but most notably in the formation of accretion disks and large streams of relativistic plasma we call jets. The most energetic jets are consistently found in a subclass of active galactic nuclei (AGN) called blazars, whose jets are oriented within a few degrees of the Earth's line of sight, making them unique sites for studying extreme astrophysics and strong gravity. AGN with jets are also possibly responsible for the production of neutrinos and ultra-high energy cosmic-rays (UHECR) reaching energies >10^{20} eV. Particle physics at such high energies is not completely known, which makes supermassive BHs (SMBHs) great test beds to probe pressing fundamental questions across physics and astrophysics. SMBHs are notorious for their high-energy emission from X-rays to very-high energy (TeV) γ-rays as well as their explosive transient behavior that manifests itself in the so-called Tidal Disruption Events (TDEs). Drastically different theories have been proposed to explain the observed behavior of these systems. So far, observations have not been enough to settle the debate.

Our current understanding of TDEs and blazars

Accretion disk formation in tidal disruption events – A TDE occurs when a star passes very close to a SMBH in the centre of a typically quiescent galaxy. The tidal forces from the BH disrupt the star, a portion of which is pulled inwards forming an accretion disk. The formation of the accretion disk is observed as a flare from optical to X-rays with the spectrum typically peaking in the ultraviolet (UV) -- soft X-rays lasting from months to years (Rees 1988). TDEs offer a completely new avenue of studying early accretion disk and jet formation not available to any other SMBH system. Observationally, there are three main classes of TDEs: X-ray-detected (bright in X-rays), optically-detected (undetected/faint in X-rays) and TDEs with a jet (radio, X-ray and sometimes γ-ray bright). The origin of the different types of TDEs and what their differences reveal about the process of accretion disk formation are poorly understood. Currently, the dominant models suggest either fast accretion disk formation and reprocessed X-ray to UV-optical emission ("reprocessing scenario" e.g., (Metzger & Stone 2016) or slow accretion disk formation by tidal shocks ("tidal shock scenario" (Shiokawa et al., 2015). Differentiating between these two scenarios holds the key to a deeper understanding of early accretion disk and jet formation. Knowledge of the accretion disk formation mechanism will lead to much better constraints on the mass of the central BH (e.g., Mockler et al., 2019, Ryu et al. 2020). Given that TDEs occur in low-mass SMBHs (<10^7 M$\odot$, for larger BHs the disruption happens inside the event horizon making it invisible), this will ultimately constrain the BH mass function in the so far unconstrained 10^5-10^6 solar mass range, which is particularly important for models of structure formation and BH growth. It will also tremendously increase our ability to detect the so far elusive intermediate mass BHs in the centers of dwarf galaxies. Understanding the intricacies of jet launching will have significant implications for supermassive BHs and possibly answer decades old questions on jet composition, as well as the role of BH spin and magnetic field. Therefore, understanding tidal disruption events will have a significant impact on an number of different subfields across astrophysics and cosmology.

This has not been possible so far because the two dominant models make similar predictions for the total intensity and late-time signatures (e.g., X-ray brightening), However, their polarization properties are expected to be quite different. In the reprocessing scenario a generally low polarization degree (Π<11.7%) and stable polarization angle (χ) are expected, whereas in the tidal shock scenario the expectations are for both high and variable Π and χ. Unfortunately, TDE polarization is largely unexplored with only a handful of single epoch optical polarization measurements in the literature, most of which upper limits (Higgins et al., 2019, Lee et al., 2020, Leloudas et al., 2022, Wiersema et al., 2012, 2020). Only recently a breakthrough was achieved using the RoboPol polarimeter at the Skinakas observatory on TDE-AT2020mot (Fig. 1, Liodakis et al., 2023). AT2020mot is currently the most polarized (25%) TDE ever discovered. This high degree of polarization can only be achieved by tidal shocks forming in the very vicinity of the black hole as the stellar stream collides with itself (Fig. 2). However, it still remains unclear whether this is the standard picture for the majority of TDEs or if AT2020mot is in the minority or even unique.

High energy emission from blazars – The origin of the high-energy emission in AGN has been a highly debated open question since the first detection of 3C 273 in X-rays and γ-rays in the 1970s by NASA's HEAO A2 and ESA's COS-B satellites. In particular, AGN with jets, and specifically blazars, dominate the extragalactic γ-ray sky, accounting for more than 98% of the detected sources by the Fermi gamma-ray space telescope. Blazar emission is typically highly variable and it covers the entire electromagnetic spectrum from radio to TeV γ-rays. The low-energy emission is well-understood

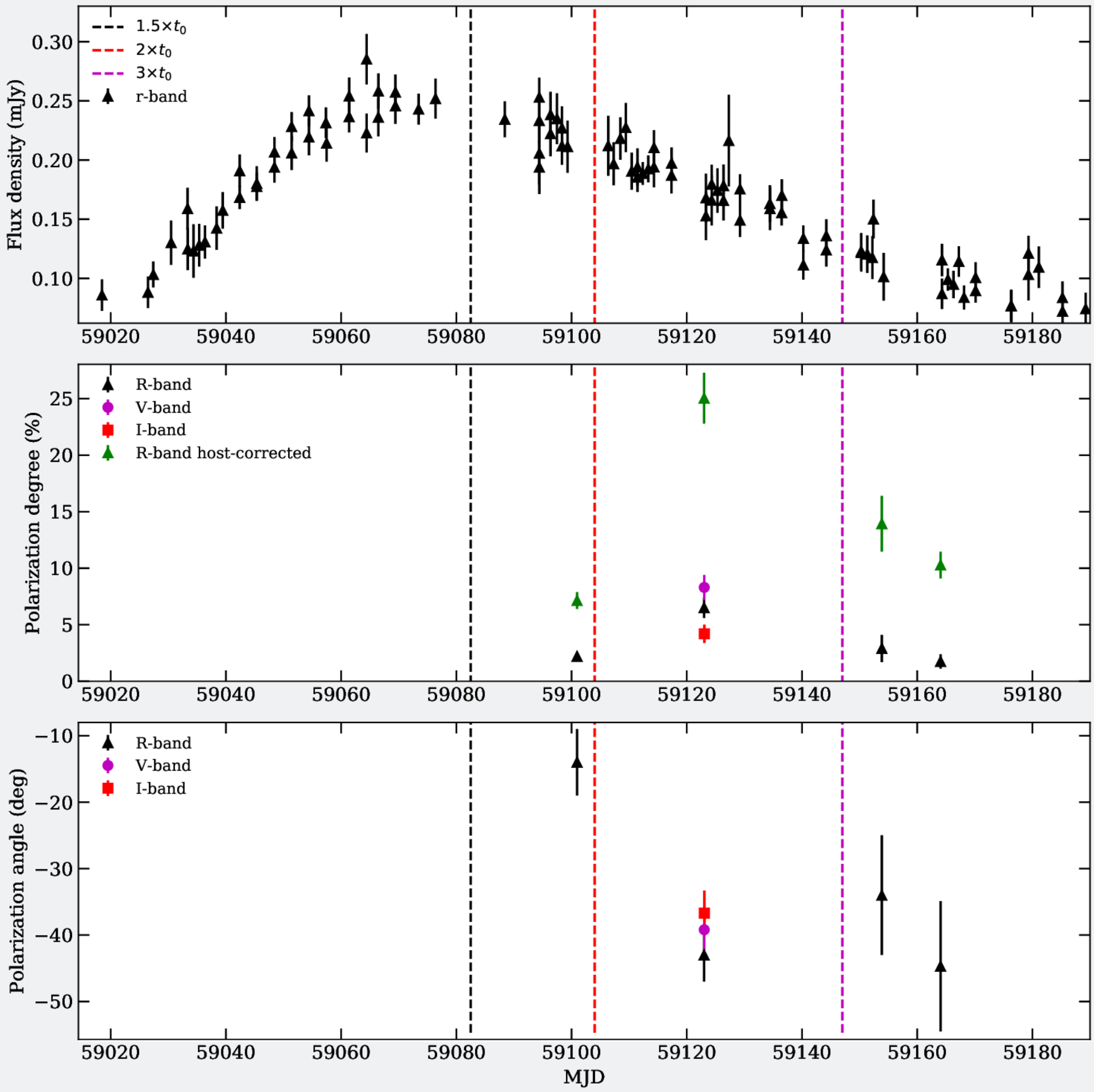

Figure 1: Optical total intensity and polarization light curve of tidal disruption event AT 2020mot. Total intensity r-band observations showing the evolution of the event (top panel), observed and host-galaxy-corrected polarization degree (middle panel), and polarization angle (bottom panel) from RoboPol. The vertical dashed lines show the characteristic timescales related to the tidal shocks that circularize the stellar debris into an accretion disk. Figure adopted from Liodakis et al., 2023.

to be synchrotron from relativistic electrons spiraling in the magnetic field of the jet. The mechanism for the high energy emission (photon energies higher than keV) is still unknown. This has been a particularly important problem since the likely association of a high-energy astrophysical neutrino event (IceCube-170922A, IceCube Collaboration, 2018) with blazar TXS0506+056. So far, this has been the only possible (~3σ) association of a high-energy neutrino with a blazar. Therefore the connection of the two remains uncertain. Neutrinos can only be produced in interactions of energetic protons or nuclei that need to have 50x more energy to produce the PeV neutrinos we observe here on Earth. This suggests that blazar jets require a significant population of relativistic protons. If that is the case, then blazars could also be accelerating UHECRs (>10^{20} eV), the origin of which is still an open question. Given that physics at such high energies is completely unknown, and orders of magnitude beyond our current laboratory capabilities on Earth, blazars, and AGN jets in general, currently provide our best chance of uncovering yet-unknown particle interaction processes. If, on the other hand, AGN jets can be excluded as the sources of high-energy neutrinos and UHECRs, it will encourage investigation of alternative astrophysical sources such as Gamma Ray Bursts, supernova shocks and pulsars and the further discussion of non-traditional sources including dark matter

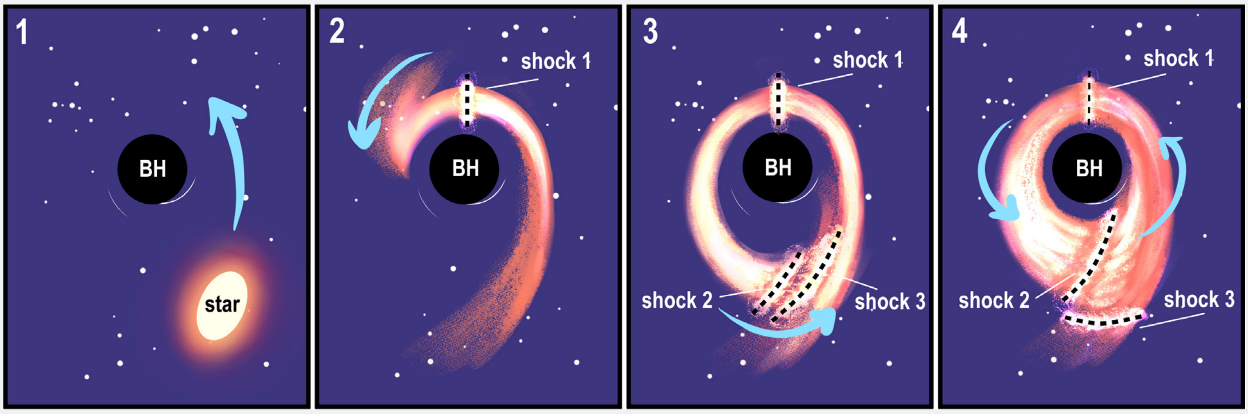

Figure 2: In a Tidal Disruption Event, a star moves close enough to a supermassive black hole so that the gravitational pull of the black hole bends the star until it is destroyed (image 1). The stellar matter from the destroyed star forms an elliptical stream around the black hole (image 2). Tidal shocks are formed around the black hole as the gas hits itself on its way back after circling the black hole (image 3). The tidal shocks create bright outbursts of polarised light that can be observed in optical and ultraviolet wavelengths. Over time, the gas from the destroyed star forms an accretion disk around the black hole (image 4) from where it is slowly pulled into the black hole. The image is not to scale. (Credit: Jenni Jormanainen FINCA/UTU)

candidates and processes occurring in the early Universe.

High-energy polarization can provide invaluable insight into the jet composition and particle energization processes. This so far has not been possible, however, on December 9, 2021 NASA successfully launched the Imaging X-ray Polarimetry Explorer (IXPE). X-ray polarization observations made available through IXPE offer a new window to the Universe and a unique tool to study the high-energy emission and jet composition as different high-energy emission models have very different polarization signatures. The first observations of supermassive black holes (and specifically blazar Markarian 501) from IXPE revealed that particles are energized in shocks (Fig. 3, Liodakis et al., 2022). As particles travel downstream from the shock, they first emit X-rays because they are extremely energetic. Moving farther downstream, through the turbulent jet regions away from the location of the shock, they start to lose energy, which causes them to emit less-energetic light like optical and then radio waves. This is analogous to how the flow of water becomes more turbulent after it encounters a waterfall – but here, magnetic fields create this turbulence. This results in a near exponential rise of the polarization degree towards higher frequencies (Fig. 4), which is not possible through alternative models. More recent observations of IXPE of the most powerful blazars found that the jet emission is most likely dominated by relativistic electrons with little to no contribution from protons (Peirson et al., 2023). However, all the IXPE observations have been performed when sources where on an average flux or even quiescent state, hence whether these results hold during the extreme outbursts blazars often find themselves, remains to be seen.

A unified approach to understanding BH processes has become paramount

TDEs and AGN jets offer different avenues of studying plasma/particle processes around BHs, across BH masses and cosmic time, each with their own advantages and limitations. Together, they can offer a comprehensive view of the phenomena associated with BHs. So far, measurements of intensity and spectral variability have proven inadequate to differentiate between models. Polarization offers an alternative, powerful, and so far unexplored tool. There are currently two major open questions at a precipice of a breakthrough in black hole studies: *What is the mechanism of accretion disk and jet formation?* and *How do relativistic jets accelerate high-energy particles?*

What is the mechanism of accretion disk and jet formation?

The presence of accretion disks and jets is ubiquitous in BH systems detected through their electromagnetic output. TDEs are the only observable BH systems where we can study the very early accretion disk formation and onset of a jet on convenient timescales of a few weeks. We are only beginning to understand these processes through optical polarization (Liodakis et al. 2023), but important open questions remain: Why is the accretion disk formation fast in some systems an slow in others? Are optical and X-ray TDEs governed by different accretion disk formation mechanisms? What is the role of the mass of the disrupting black hole? What are the conditions necessary to form a jet? These questions cannot only be addressed by a comprehensive multiwavelength monitoring of TDEs including polarization. So far, the limitation in studying TDEs has come from the small number of known events as well as our ability to classify TDEs before their emission reaches its peak. However, the advent of large scale optical surveys like the Zwicky Transient Facility (ZTF) have tremendously increased the number of known events, with currently ~15 events identified every year. The coming of Vera C. Rubin's Legacy Survey of Space and Time (LSST) promises to revolutionize time domain astronomy and our view of the Universe. The discovery expectation for LSST is 10-20 TDEs per night. The next few years are bound to see major breakthroughs in our understanding of accretion flows around supemassive black holes.

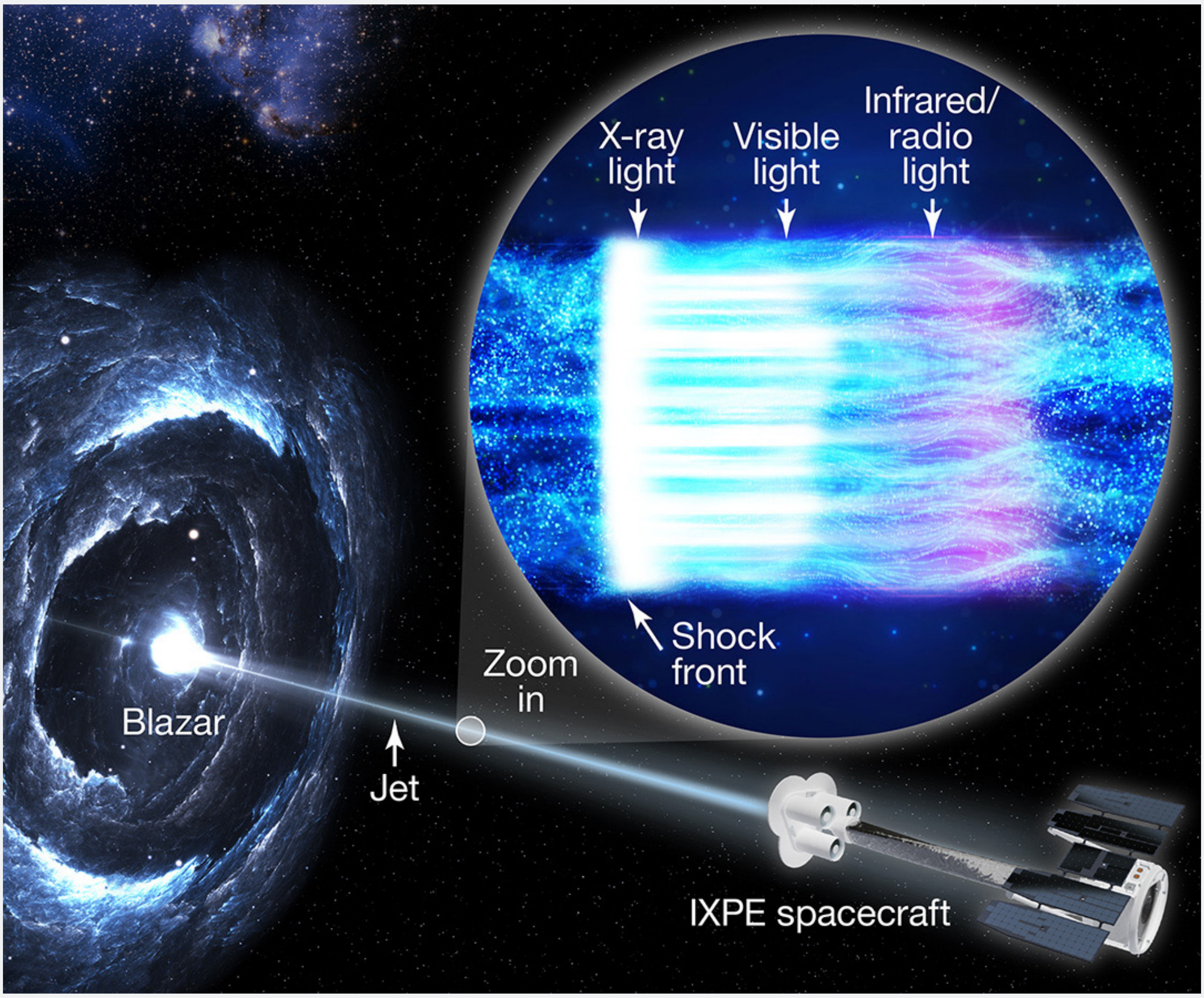

Figure 3: This illustration shows the IXPE spacecraft, at right, observing blazar Markarian 501, at left. The inset illustration shows high-energy particles in the jet (blue). When the particles hit the shock wave, depicted as a white bar, the particles become energized and emit X-rays as they accelerate. Moving away from the shock, they emit lower-energy light: first visible, then infrared, and radio waves. Farther from the shock, the magnetic field lines are more chaotic, causing more turbulence in the particle stream. Credit: Pablo Garcia (NASA/MSFC)

How do relativistic jets accelerate particles?

Evidence suggests that variations in the magnetic field, traced by polarization, are the most likely driving mechanism for particle acceleration in jets. There is strong evidence from the RoboPol project that link the jet's polarization behavior with high-energy emission (e.g., Pavlidou et al., 2014, Angelakis et al., 2016). For example, there is a strong temporal relation between Electric Vector Polarization Angle (EVPA) rotations and γ-ray flares (e.g., Blinov et al., 2018, Liodakis et al., 2020). EVPA rotations are coherent rotations of the polarization plane for hundreds of degrees, often more than 360º. They are so far only found in BH jets, with unclear origin. One of the proposed mechanisms for magnetic field variations is shocks. Shocks can be formed due to instabilities or inhomogeneities in the plasma and jet-environment interactions. They are characterized by correlated variability across the electromagnetic spectrum often producing polarization flares. Several models attribute Electric Vector Polarization Angle (EVPA) rotations to the propagation of shocks along the jet either through helical trajectories, bent jets, or light travel effects (e.g., Marscher et al., 2008, Zhang et al., 2014, Liodakis et al., 2020). While the shock-in-jet interpretation has been the favorite model of the AGN community, it is not without its limitations. An example is the very fast – minute timescale – variability observed in γ-rays (e.g., Ackermann et al., 2016) which is hard to reconcile with our current understanding the jets. Shock-in-jet models naturally assume that the shock affects the entire cross section of the jet, hence the timescale of variability is limited by the light-crossing time. For typical jet parameters, that variability timescale is >12 hours (longer than a typical observing night). Intranight variability in total intensity has been observed in a handful of blazars, however, this is generally attributed to the superposition of different emission regions within a turbulent jet (e.g., Marscher 2014). The alternative particle acceleration mechanism is magnetic reconnection. Magnetic reconnection has been recently gaining favor among the community since it can reconcile a few aspects of the puzzling blazar behavior. For example, it can produce correlated variability on a broad variety of timescales due to the coalescence of different size magnetic islands (or plasmoids, Petropoulou et al., 2017). A statistical investigation of the 3-year observations of the RoboPol sample demonstrated that EVPA rotations on faster timescales (<12 hours) might exist (Kiehlmann et al, 2021). However, there has never been so far a systematic study of the intra-night polarization variability in jets.

The **B**lack h**O**le **O**ptical-polarization **T**im**E**-domain **S**urvey (BOOTES) is a recently selected ERC Starting grant project that will start at the Institute of Astrophysics – FORTH in 2024. BOOTES aims to tackle the aforementioned questions by bringing together an unprecedented view of polarization in both steady and transient BH systems on timescales that have so far been unattainable. This will be achieved by using unique world-class polarimeters like RoboPol (optical) and IXPE (X-rays) as well as an unprecedented observing time commitment by the Skinakas observatory. In the next few years, BOOTES aims to deliver the first comprehensive monitoring of TDEs in polarization and the first systematic very-high-cadence polarimetric monitoring of relativistic jets, thus unraveling BH accretion, jet launching and particle acceleration in the most persistently bright objects in the known Universe.

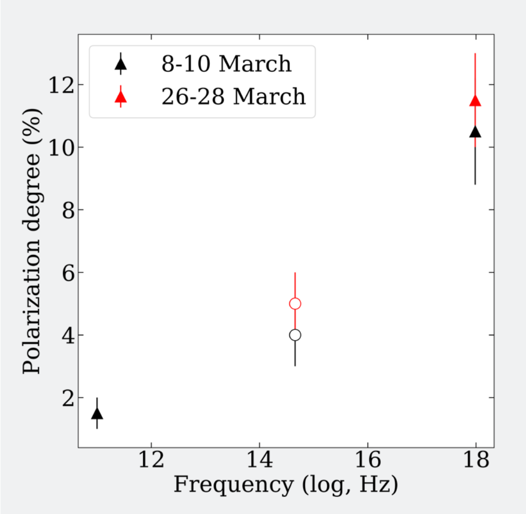

Figure 4: Polarization degree versus frequency for blazar Mrk 501. The red and black points are for two different observations in March 2022. The open symbols are the intrinsic optical polarization after correcting for the depolarizing effect of the host-galaxy. The near-doubling of the polarization degree is the result of the emitting particles traveling through more and more disordered magnetic field regions as they move downstream from the shock front. Figure adopted form Liodakis et al., 2022.

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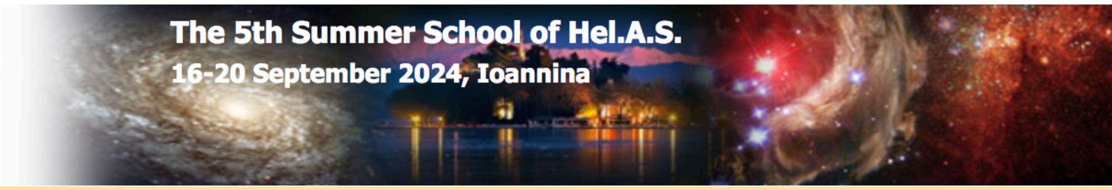
HELLENIC ASTRONOMICAL SOCIETY



The Hellenic Astronomical Society, in collaboration with the University of Ioannina, under the initiative to offer knowledge and scientific training to the younger members, graduate students and young postdoctoral researchers of the Society, is organizing the 5th Summer School entitled: "Magnetohydrodynamics (MHD) in Astrophysics" in Ioannina, from the 16th until the 20th of September 2024.

The invited speakers of the school and the topics of their lectures are:

C. Alissandrakis (University of Ioannina)
"The Universe is Made of Plasma and Magnetic Field"

A. Anastasiadis (National Observatory of Athens)
"MHD as the Backbone for Space Weather Prediction"

V. Archontis (University of Ioannina)
"MHD, Solar and Stellar Activity"

I. Contopoulos (RCAAM of the Academy of Athens)
"MHD with Physics Informed Neural Networks"

K. Gourgouliatos (University of Patras)
"MHD in extreme Astrophysical Environments"

K. Moraitis (University of Ioannina)
"Theory and Applications of Magnetic Field-Line Helicity in Solar Physics"

A. Nindos (University of Ioannina)
"Magnetic Helicity: Applications in Solar Physics"

K. Tassis (University of Crete & FORTH)
"MHD of the Interstellar Medium"

G. Throumoulopoulos (University of Ioannina)
"MHD of Laboratory Plasmas: Crossovers with Astrophysics"

K. Tsinganos (University of Athens)
"Introduction to MHD"

N. Vlahakis (University of Athens)
"MHD Instabilities"

L. Vlahos (University of Thessaloniki)
"MHD Turbulence and Particle Energisation"

J. Zhuleku (University of Ioannina)
"Heating of Solar and Stellar Coronae"

Moreover, the following practical tutorials/exercises will be coordinated by the lecturers:

I. Dimitropoulos & I. Contopoulos:
Solution of a Simple Physics Problem with Physics Informed Neural Networks (PINNs)

K. Gourgouliatos:
Numerical Methods for MHD -Force-free equilibria via relaxation methods. -Time dependent problems: upwind schemes - flux limiters. Demo of AMR-VAC MHD code

K. Moraitis, J. Zhuleku, V. Agalianou, A. Giannis:
Visualization and Analysis of MHD simulation output

A. Nindos & N. Vlahakis:
Problem Solving in MHD

https://helas.gr/school/2024/
E-mail: mhdschool24@gmail.com

Back issues of Hipparchos

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