HIPPARCHOS

The Hellenic Astronomical Society Newsletter
Volume 3, Issue 4

ISSN: 1790-9252

Contents

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Volume 3, Issue 4 • July 2021

ISSN: 1790-9252

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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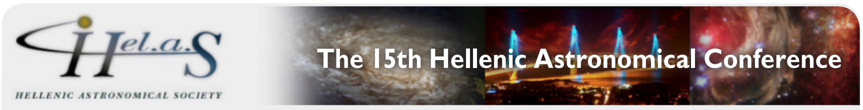

The Hellenic Astronomical Conference, organized by the Hellenic Astronomical Society (Hel.A.S.), is the major scientific event of the greek astronomical community. The Conference, which takes place every two years in a different part of Greece, typically brings together over 100 scientists with research interests in Astrophysics, Planetary Science and Space Physics.

The 15th Conference of Hel.A.S. was originally planned to take place in Patras, from 5 to 8 July, 2021. However, the persistence of the COVID pandemic forced us to host the conference virtualy.

We would have much preferred to seeing you in Patras, but we hope to least see you online instead!

Sponcored by:

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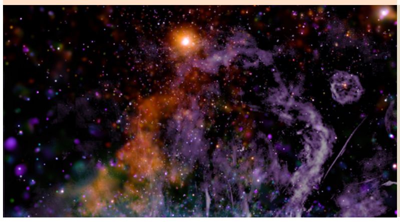

Cover Image: The Galactic Center: A detailed panorama explores regions just above and below the galactic plane. Different bands of X-rays from the Chandra Observatory (orange - hot, green - hotter, purple - hottest) have been combined with radio data (gray) from the MeerKAT telesccope. These data reveal threads of superheated gas and magnetic fields near the center of the Milky Way. **Image Credit:** X-ray: NASA/CXC/UMass/Q.D. Wang; Radio: NRF/SARAO/MeerKAT.

Message from the President

Over this past year, we have all been experiencing the abrupt changes in our daily lives imposed by the pandemic and several of us have had family and friends who have become sick. Moreover, the way we work, teach, and do science has been modified and in the process we became experts in using ZOOM, Webex and eClass along with a variety of other teleconference tools.

Despite these challenges, our training in the new "tools of the trade" also enabled new opportunities. We have attended lectures and seminars from institutes across the globe and participated in conferences remotely. Sharing information in a reliable and user-friendly manner has become much easier for all. Our Society, following the popular trend, commenced a monthly virtual colloquium. A committee of three members of the Governing Council – Nektarios Vlahakis, Spiros Patsourakos and Kostas Tassis – selected a group of distinguished colleagues who presented 9 very interesting colloquia this past academic year. These were typically attended by over 70 of our members and are now available as recorded videos in the YouTube channel of our Society. I would like to personally thank everyone involved, and in particular the speakers who invested their time to share with us their results, and I do look forward for these colloquia to continue for many year into the future.

However, due to the restrictions of the pandemic, it was not possible to meet in person in Patras during the 15th Conference of our Society, as it was originally planned. Our conference, like many others, will be held "virtually" during the second week of July 2021. This appears to have facilitated participation since over 200 astronomers from 24 countries, both members and non-members of Hel.A.S., have registered to attend it, making it the largest ever conference organized by our Society. The Scientific Organizing Committee has selected four exceptional scientists as plenary speakers, Dr. Francisco Colomer (JIVE, The Netherlands), Dr. Athena Coustenis (Obs. de Paris, France), Prof. Avishay Gal-Yam (Weizmann Institute, Israel) and Prof. Kostas Kokkotas (Univ. of Tuebingen, Germany), and worked hard to prepare a dense and diverse scientific program. In addition, the Governing Council decided to name one of the plenary lectures as "John H. Seiradakis Plenary Lecture", in memory of Prof. John Seiradakis who passed away last year. As we all know Prof. Seiradakis played a critical role in founding the Hellenic Astronomical Society and also was the Secretary of the Society from 1994 until 1998 and President from 1998 until 2002.

Over the past year, the Society, thanks to the investment of time and energy of several members, also obtained a more prominent presence in the social media. We now maintain an active Facebook page, where we share science news and information about all major astronomy events that take place in Greece, as well as an Instagram and Twitter account. Moreover, Hel.A.S. supported the public outreach activities of a dynamic group of Junior Members, who established the "2 minute Science" page, both on the web and on Facebook, in order to share with the general public in Greece their excitement about astrophysics and space physics. I do hope that they keep their enthusiasm and with the help of the next generation of astronomy students and postdocs will continue to provide, in Greek, interesting and high quality information about astronomy to our fellow citizens.

The Vice Chair of the Society, Prof. Nektarios Vlahakis, was also responsible in selecting and editing the four invited articles on pertinent areas of astrophysics, which appear in the present issue of Hipparchos. Prof. Theoharis Apostolatos is presenting the latest results in the quest for gravitation waves, Dr. George Leloudas is sharing with us some of the wonders of the transient sky, Dr. Anastasios Anastasiadis with Dr. Athanasios Papaioannou provide the latest information on tracing energetic particles emanating from the Sun, and Dr. Angelos Tsiaras is describing the ongoing efforts in characterizing the atmospheres of exoplanets, on the eve of the upcoming launch of the James Webb Space Telescope from NASA and the Ariel mission from ESA. I am certain that we will all enjoy and learn a lot reading them.

Vassilis Charmandaris
President of Hel.A.S.

Sensing the pulsations of empty space

by **Theocharis A. Apostolatos**
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1. Introduction

Struggling for almost a decade, after the annus mirabilis when he formulated Special Relativity, Albert Einstein moved on to formulate General Theory of Relativity, which was completed in 1915. Although the idea of a curved space-time sounds rather simple, and well known, today, it was a radical idea at the dawn of the 20th century and full of surprises. Famous physicists, like Lev Landau, considered the idea of Einstein as a unique idea in the history of Physics and have jealously described General Relativity as *"probably the most beautiful of all existing physical theories"*. Although the basic idea was conceived by Einstein rather early, it took him years to overcome the mathematical obstacles before he presented it in its right, final form. Actually, it was David Hilbert, a famous mathematician inspired by long discussions with Einstein, who managed to formulate General Theory of Relativity a few days before Einstein, following the much easier path of least action principle.

At first the Einstein equations, as they came to be known, were mostly neglected by the physical community, since the mathematical notions involved in the theory were not included in the basic education of physicists at the time. Apart of a handful of weak-gravity relativistic results expressed as tiny corrections of newtonian gravity, that eventually turned Einstein into an established figure in sciences, physicists could not work out but a few, though oversimplifying symmetrical physical systems based on the new theory. The mathematics involved were too complicated. Soon General Relativity was considered a field of mathematics with no much connection to the physical world, apart of its innovative interpretation of gravitational force. On the other hand, great mathematical ideas with applications in various physical theories sprung from the new field, like Noether's theorem, substantial developments in differential geometry, the tensor calculus by Levi-Civita etc.

The idea of waves permitted by this new field (the field of the metric of the space-time itself) concerned Einstein himself, from the very beginning. In analogy to Maxwell equations which permitted the existence of electromagnetic waves, Einstein felt that his new set of equations should allow for similar type of waves. However, the fact that the coordinates one could use to map space-time, apart of being continuous and differentiable, were completely free, led him to a very difficult situation. One should somehow discern the true waves if that had any meaning from the fictitious waves showing up just as an artifact of choosing crazy coordinates. Einstein faced that problem and was soon led to wave solutions moving at any possible speed! As Arthur Eddington, one of the first believers of Einstein's theory, commented "gravitational waves should propagate at the speed of thought". Einstein was so puzzled that for almost two decades, he was opposed to the idea that there was any kind of propagating gravitational waves corresponding to some real physical context as energy carriers. After the repeated denial of the existence of gravitational waves by Einstein, he finally conceded they are real, convinced by his own colleagues (Infeld, Rosen) and other physicists and mathematicians.

The lack of physical experiments, where one could measure the differences between the new theory and the celebrated for three centuries newtonian theory of gravity, as long as the advent of quantum mechanics lead General Relativity to remain confined in a few small groups of mainly mathematicians, scattered around the globe. Gravitational waves were not an exception. In the famous book "Classical Theory of Fields" of Landau and Lifshitz [1] that was first published during the World War II, and was translated in English in the 50's, it is noted that the amount of energy radiated by gravitational waves in he case of a binary system would be of the order of 10^{-12} of the total energy of the system itself, and thus the time scale expected to see its effects on the motion of the binary would be of cosmic order. No one was crazy enough to suspect that something so tiny would ever be observed.

2. The golden era of General Relativity and a bold experimental device

In the 50's a new generation of physicists of high caliber, such as Bondi, Pirani, Wheeler, Feynman, DeWitt, Hawking, Penrose, and others, showed special interest to relativity. Gravity, along with the dreams of space exploration, was again an exotic field that allured

Figure 1: *Joseph Weber working on the electronics of his bar detector.*

many brilliant minds. While theoretical issues, like what is the energy content of gravitational waves, were still puzzling physicists, a young collaborator of Wheeler, Joseph Weber wrote with Wheeler a paper describing a thought experiment that could be used as a detecting device of gravitational waves. Later on, in the 1960's, Weber built a resonant detector in Maryland, consisting of pure aluminum cylinders that were constructed to resonate at 1661 *Hz*, when a gravitational wave signal of that frequency hit them. The cylinders were seismically isolated, and piezoelectric crystals around the "bar detectors" were adjusted to measure tiny oscillations of their length. Weber, who was a master in electronics, build the whole device by himself, and made it capable to detect gravitational waves of strain 10^{-16} [2]. As another Columbus he embarked on this journey without knowing either what are the possible sources of such waves, neither their physical characteristics (their frequency and their amplitude). He picked up a frequency (and built bars having that specific normal mode eigenfrequency) in the range where he thought various astronomical sources, like a star with a bump undergoing gravitational collapse, could emit substantial gravitational waves. At that time gravitational radiation was still an open issue, full of controversies, and with no sufficiently rigid scientific results. Weber was bold enough to believe that mankind was ready to detect such miniscule deviations from flat metric and he had the ambition to be the pioneer of this effort. In 1969 Weber declared that he had detected for the first time gravitational waves from cosmic sources and subsequently, a long series of such "detections" followed during the next few years. Weber built a second bar-detector in Chicago, in order to make sure that he counted only the coincident signals in both detectors, thus disregarding any spurious electronic noise in each device. Unfortunately his findings were not confirmed by other experimentalists who were inspired by Weber's effort and built their own bar detectors. None was able to reproduce his results, even though one of these new detectors were built at exactly the same size as Weber's detector. Although the scientific community eventually rejected Weber's discovery, Weber continued to believe that he was observing gravitational-wave signals. It is remarkable that part of the doubt about Weber's claims was driven by theory: If Weber's detectors were observing such signals from so distant sources the corresponding energy emitted by them would be huge and our galaxy should disintegrate in a much shorter time than its age. Despite this negative environment, some theorists, holding Weber's work in high regards, thought of imaginative, but rather exotic, type of sources that could somehow reconcile Weber's claims and theoretical objections. I remember Kip Thorne in a Pacific coast gravity conference in 1994 trying to reconciliate Weber's opponents with Weber's exaggerations regarding his findings, in a hot discussion following Weber's presentation.

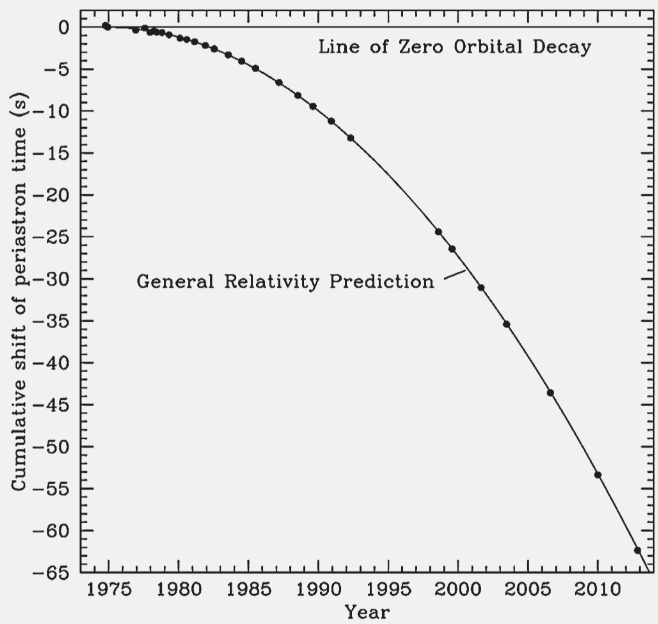

Figure 2: *The evolution of the orbital period of PSR 1913+16 for almost 4 decades. The solid line is the theoretical prediction of General Relativity, while the dots represent actual observations. The error bars are so small that are not discernible. The graph is adapted from the paper of Weisberg and Huang* [4] *in 2016.*

Nowadays, the detections of Weber are unequivocally rejected by the community. However all recognize him as the father of gravitational-wave research (as Misner put it). If he was not bold enough to start this enterprise, the actual detection of gravitational waves would probably be delayed by at least a decade.

In 1974 another new finding related to gravitational waves showed up. Hulse and Taylor discovered the first pulsar in a binary system, now known as PSR 1913+16. The 59 *ms* pulsar involved, was found to be modulated with a period of 7.75 *h*, indicating the presence of a close compact companion around which the pulsar is orbiting. According to General Relativity such a close binary is expected to radiate gravitational waves leading to an adiabatically shrinkage of orbital radius, and consequently to a slow increase of its orbital frequency. Weisberg and Taylor followed the evolution of the orbital modulation of PSR 1913+16 for a few years and found that the theoretical expectation of General Relativity was accurate to the level of 1.8σ, corresponding to a tiny 76.5μs/yr decrease in orbital period.

The paper published by Weisberg and Taylor [3], with all these detailed observations, was quite convincing that gravitational radiation was a real phenomenon with measurable impact on some astrophysical systems, more specifically for binaries consisting of compact objects like neutron stars. For the first time the scientific community had in hand relativistic evidence regarding strong gravitational fields. All the previous tests of General Relativity, like the ones regarding our Solar system, were weak field approximations of Einstein's theory.

3. Order of magnitude estimations

In order to have a feeling of the numbers involved in the radiation reaction of a gravitational system, we give here the famous quadrupole formula introduced by Einstein in a paper of 1918 [5].

$$\frac{dE_{GW}}{dt} = \frac{G}{5c^5}\dddot{Q}_{ij}\dddot{Q}_{ij}\,. \qquad (1)$$

This is the formula that was disputed for many years, as was mentioned earlier, and was later derived in the book of Landau and Lishitz for binaries, following a rather dubious methodology. It gives the rate of energy in the form of gravitational waves emitted by a physical system moving under its own gravity. *Qij* is the the quadrupole moment of the system, while the triple dots denote a triple derivative with respect to time. The *G, c* constants are the usual gravitational constant and the speed of light respectively. This formula is the analogue of dipole radiation in electromagnetism emitted from accelerating charges.

The factor in front of the expression G/c^5 is so small, of the order of 10^{-53}(joules/s)$^{(-1)}$ that nobody would ever thought of ever being able to observe any effect on such systems due to gravitational radiation. The rest part of the formula, which is related to the physical characteristics of the system itself, should bring forward the rest dimensions, (joules/s)^2, to get the final answer. What if the physical parameters of the systems were normalized in such a way that the final formula had the factor G/c^5 inverted with the right dimensions of power, and the rest were simple dimensionless numbers characterizing how relativistic is the system, namely v/c (the velocity of the parts of the system) and R/R_S (how large compared to its Schwarzschild radius R_S is the system). Working out the details of this magical inversion, we finally arrive at an order of magnitude for the rate of energy emitted

$$\frac{dE_{GW}}{dt} = \frac{c^5}{G}\left(\frac{R}{R_S}\right)^2\left(\frac{v}{c}\right)^6. \qquad (2)$$

The tiny amounts of energy, at first glance, turn out to be tremendous for suitable systems.

The moral of this simple, back-of-the-envelope calculation shows that as long as the system consists of very compact objects with $R/R_S = \mathcal{O}(1)$, like neuron stars or black holes, that are moving so close to each other that the velocities involved are close to the speed of light, gravitational radiation emission could make these systems the most explosive machines in the Universe. On the other hand the high powers of both undimensional terms in eq. 2, make it rather implausible that one would ever be able to observe significant gravitational radiation signals from macroscopic terrestial, or near Earth sources despite, the much shorter distances involved (the normal objects are far from compact, and are moving with highly non-relativistic velocities).

4. The LIGO-VIRGO era

In the late 80's a few visionary physicists believed that time had come for building devices capable of detecting gravitational waves. Rainer Weiss, Vladimir Braginsky, Kip Thorne, and Ronald Drever embarked on a wonderful journey to construct huge interferometers that could work as broad band (in contrast to those of Webers) gravitational detectors. The idea was simple: One should hang 3 test masses-reflectors in the form of pendulums (forming a Γ). Along the two long arms between the corner mass and the two other masses, monochromatic light would travel up and down. Whenever a gravitational wave hits the two arms it will make the arms oscillate in opposite phase (due to the tidal nature of gravity waves). The interference pattern formed by the two beams should follow the time evolution of the signal itself.

On the other hand there were numerous technical issues, as well as

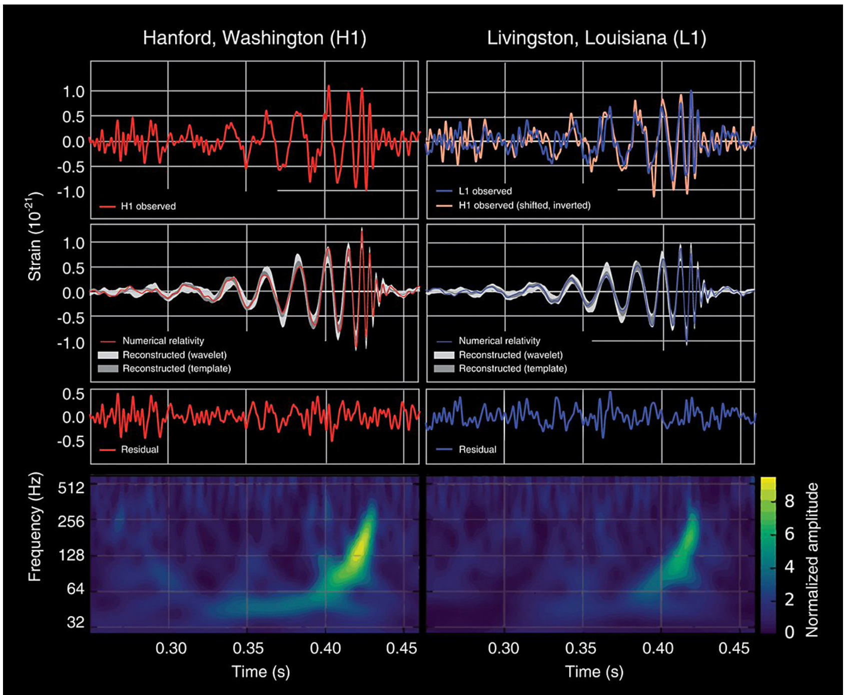

Figure 3: On the first line of diagrams the raw data of GW150914 signal are shown (the left is from Hanford LIGO, while the right is from Livingston LIGO). To emphasize the coincidence, the left diagram is superimposed on the right one after a suitable time shift accounting for the signal to travel from one site to the other. The second line of diagrams are theoretical waveforms of the signal itself that matches the raw data of each detector. The signal has the characteristic chirp for both amplitude and frequency, representing the inspiral orbit of the two black holes, up to the point where the two horizons of the black holes merge into a single one. Then the final, highly deformed, new black hole oscillates violently and, in a few hundredths of a second, it finally rests in peace as a quiescent spinning black hole, by radiating away all its deformations. The third line presents the difference between the actual signals and the best fitting theoretical waveforms of line two. The fourth line is a spectrogram showing up the chirping evolution of the frequency, along with the intensity of the signal.

funding ones (of the order of a few hundred million US dollars). The National Science Foundation of US was convinced that the endeavour was worth the money, since gravitational waves would open up a new window to observe the cosmos. After a long experimentation in small laboratories both in Caltech and MIT, two four by four kilometers interferometers were built in the two corners of USA; the Hanford LIGO, and the Livingston LIGO [6]. The locations were chosen so that the two sites were as far apart as possible in order to obtain some useful information about the direction of the signal, by measuring the small differences in arrival time of the detected signals. Also the arms between the two sites are forming an angle close to 45° in order to be able to pick up the two different polarizations encoded in a signal.

A similar third interferometric detector VIRGO, named after the VIRGO cluster, with three kilometers arms was built in Pisa, Italy and after 2007 they have agreed to share their data with LIGO, and publish jointly their results.

The operation of LIGO-VIRGO lead to the first detection of gravitational waves (actually VIRGO was not operating at the time), the so called GW150914, a few days before the formal beginning of the research phase. Although the signal was quite strong, it took the LIGO team five months to ensure that the detector output was clean and no other physical explanation could justify this characteristic chirping signal, lasting a few tenths of a second. As is well known, this great event drew international publicity, and marked the commencement of a new era, where scientists were equipped with a new type of device to sense the cosmic, violent events that are not accessible through electromagnetic radiation.

5. The current status of the LIGO-VIRGO observatory of the dark violent universe

Since the first successful detection of gravitational wave signals, around 50 candidate signals have already been reported; most of them are black hole–black hole binaries, with masses in the range of a few ≃ 10 to a ≃ 100 solar masses. There are also a couple of neutron star–neutron star binaries or neutron star–black hole binaries among the detection events. One of them, the GW170817, consisted of two neutron stars, that emitted strong electromagnetic radiation a couple of seconds after their collision. Such combined detection by gravitational wave and electromagnetic wave detectors was extremely fruitful. It gave gravitational-wave astronomers the opportunity to pinpoint the source with high accuracy. Furthermore the evolution of the signal, when the tidal effects arising on each neutron star from its companion are strong, depends highly on the details of the actual equation-of-state governing the behavior of neutron-star material. A greek young scientist, Katerina Hatziioannou, is one of the leaders in the quest of putting constraints in the equation-of-state of neutron stars, based on the tidal deformability of neutron stars which is encoded in the gravitational wave signals from neutron star–neutron star mergers [7].

6. The future of Gravitational-Wave Astronomy

During the last decade new gravitational -wave detectors are build around the globe (IndIgo in India, KAGRA and TAMA in Japan, AIGO in Australia), while further technological advances are planned for the existing detectors. Also new, much longer, much more sensitive ground based detectors are currently under consideration (Einstein telescope, Cosmic explorer). Finally there are plans to fly spaceborne detectors (like LISA), that would be able to detect gravitational waves for massive black holes, since these detectors are most sensitive at frequencies two orders of magnitude lower than their terrestial counterparts.

In a few years the gravitational-wave detectors will offer scientists a new point of view of the Universe, "hearing" the dark corners that cannot be seen, and enriching our view about the cosmos, its constituents, and its history. A new branch of Astronomy has been born.

Acknowledgement

Most of the stories written here are taken from the great book "Traveling at the speed of thought" of Daniel Kenefick [8]. Daniel was a very gentle graduate colleague of mine with whom I had the chance to spend 4 years being both members of Kip Thorne's group. I would like to thank him for offering me his book and made me feel that we were both small parts of this great adventure.

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A revolution in transient astrophysics

by **Giorgos Leloudas**

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It is not an exaggeration to state that transient astrophysics has overgone a revolution during the last decade. As a matter of fact, even the term *transient astrophysics* was not widely used before then. So what is transient astrophysics? It is difficult to make a strict definition but, generally speaking, it is the study of astrophysical phenomena of transient nature. From this definition we implicitly exclude periodical events (such as variable stars) or objects in the solar system (e.g. asteroids, comets). Usually, transients are implied to be catastrophic events, such as supernova explosions or tidal disruptions of stars, although this is not always the case.

A few years ago, this field was almost synonymous with the study of supernova explosions. At the turn of the century, supernovae (SNe) were a consolidated field of study that was experiencing a rapid increase of interest due to the discovery of the acceleration of the Universe. By that point, almost all supernovae belonged to well-established classes, including both thermonuclear (Type Ia), as well as core-collapse supernovae (Types II, Ib, Ic) and their subtypes (see e.g. the classification scheme of Filippenko 1997). These are fundamentally different explosions: Type Ia SNe are the thermonuclear explosions of white dwarfs in a binary system. It is these supernovae that are used as standardizable candles to measure distances across the Universe. The other supernovae result from the core-collapse of a massive star after it has exhausted its nuclear fuel and can no longer sustain its own gravity. An important point to note is that, except the supernovae discovered in cosmological surveys searching for high-redshift Type Ia supernovae, the majority of supernovae were still discovered with the same method that Fritz Zwicky introduced in the 1930s : by repeated observations of galaxies and searching for the appearance of "new" stars. The problem is that this method, which has produced extremely significant results and which is still widely used by amateur astronomers, is biased towards bright and nearby galaxies, which are typically rather massive and chemically evolved (metal-rich). Therefore, rare types of explosions, or explosions that favor different kinds of environments, were not probed by this method.

The switch to modern wide-field surveys that target the field rather than specific galaxies has proven a game changer for transient astronomy. Thanks to wide-field cameras, several sky surveys operating in the time domain are able to observe large parts of the sky and employ image subtraction techniques to find new transients, irrespective of their association to host galaxies. As a result, the number of transient discoveries has exploded since 2000 (Figure 1). The large numbers have allowed for intrinsically rare transients to be uncovered, i.e. phenomena whose rate can be as low as 1/1000 compared to common Type Ia SNe. At the same time, the galaxy-unbiased nature of these surveys has revealed a wealth of transient phenomena that were previously unknown, simply because they tend to occur in different types of galaxies (or even at large distances from any galaxy!) than those monitored before. Finally, due to the rolling nature of these surveys, it is now possible to find and characterize supernovae within the first days from explosion, allowing for novel science to be conducted.

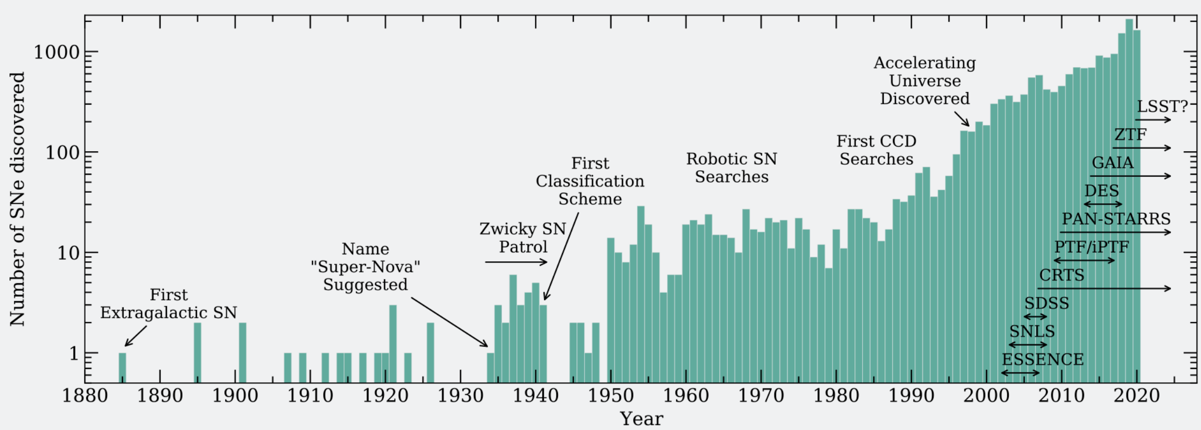

Figure 1: *The evolution of supernova discoveries through the years with a few key events highlighted. The number of confirmed supernovae has increased dramatically in the last few years (notice the y axis is logarithmic). The acronyms and arrows on the right hand side stand for different transient surveys and their years of operation (Credit: Miika Pursiainen).*

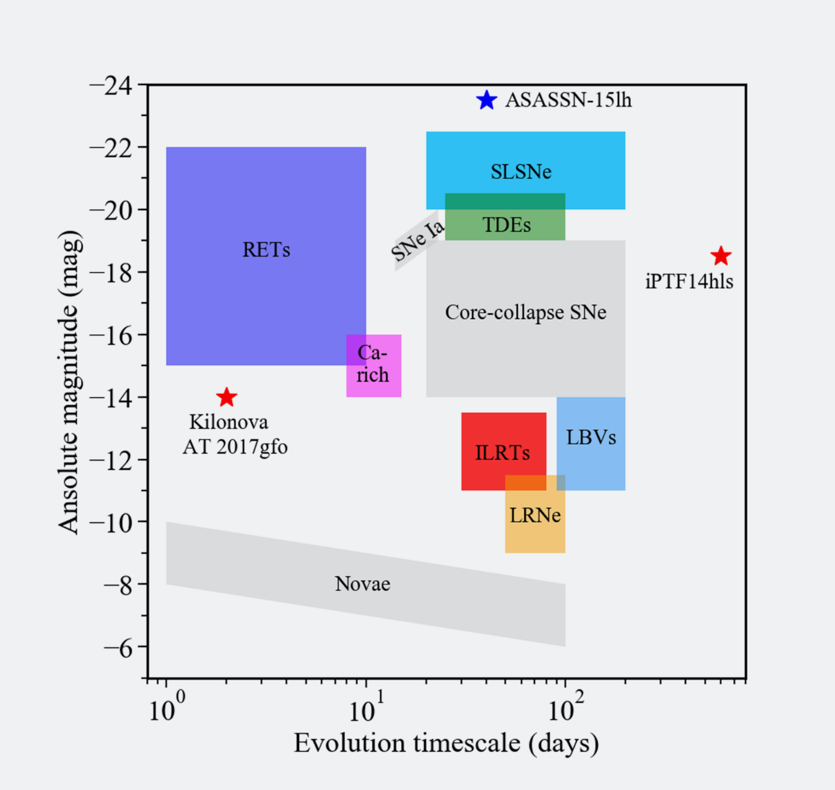

Figure 2: *Transient phase space with typical transient luminosity (absolute magnitude) on the y axis and characteristic evolution timescale on the x axis. Different types of transients occupy different regions of the phase space, e.g. the brightest events appear on the top of the graph, the faster events to the left, etc. The acronyms for different classes of transients can be found in the main text. Individual unique events are marked with a star.*

In this review, I will introduce and give a brief summary of phenomena that were discovered during this "transient revolution" and that go beyond the traditional supernova classes as these were known a few years ago. To this end, I will use the concept of the *transient phase space*, which characterizes transients depending on their luminosity and duration (Figure 2). Different types of transients occupy different regions of this phase space. I will thus focus on transients that are *brighter*, *fainter* or *faster* than the main types of supernovae (Type Ia and core-collapse). I will also address transients occurring in the nuclei of their host galaxies (tidal disruptions of stars) and I will highlight a couple of spectacular unique events. Finally, I will address a few current challenges in the field as well as future prospects.

The bright – Superluminous Supernovae

Superluminous supernovae (SLSNe) are found on the top of the transient phase space diagram as they are significantly brighter (by a factor of 10-100) than typical core-collapse or thermonuclear SNe. Up to a few years ago, the fiducial limit M = –21 mag was used to separate SLSNe from "ordinary" SNe but this hard limit is no longer in use, as it has been shown that this was just operational but without any physical meaning. Exceptionally bright SNe were occasionally discovered in the past but it was not until 2011, when Quimby et al. combined a number of objects discovered by the Palomar Transient Factory (PTF) with the enigmatic hostless transient SCP06F6, and determined their distances, that it was safely demonstrated that a distinct class of SLSNe existed showing common properties. These objects had unprecedented pre-maximum spectra dominated by absorption lines of O II that later evolved to SNe Ic (i.e. SNe without any evidence of H or He), they had broad light curves (often bell-shaped), blue colors and they were found in very faint host galaxies (often not detected). These objects are now collectively known as SLSNe I, in analogy to SNe I where "I" signifies a lack of hydrogen in their spectra. The discovery of these events sparked a huge interest as it quickly became apparent that the standard paradigm of Fe-core collapse cannot explain these events: their light curves cannot be powered by radioactive Ni^{56} as ordinary supernovae. For this reason, alternative models have been proposed, such as the powering by the spin down of a newly-born magnetar, or the collisions of H-free massive shells expelled by the progenitor star, possibly via the pulsational pair-instability mechanism (for a review on the possible luminosity sources, see Moriya et al. 2018).

During the last decade, significant observational progress was achieved in the field of SLSNe I (see Gal-Yam 2019 for a review). A first peak (a "bump") was observed before the main light curve maximum and it was later shown that such bumps are very common in SLSNe. It has been possible to perform studies of samples and show that the ejected masses are large, spanning a range of 3-30 $M_\odot$ (solar masses) pointing to massive progenitors, although suspicions exist that there could be two different sub-classes within SLSNe I ("fast" and "slow"-evolving events). Mounting evidence for the presence of circumstellar shells around SLSNe I has been inferred either by late-time interaction or indirectly by resonant echoes. Intriguingly, it has been suggested that SLSNe I obey a brightness - light curve width relation that can be standardized (Inserra & Smartt 2014), similar to SNe Ia. If true, this means that they can be used as distance indicators to measure the expansion of the Universe at much higher redshifts than SNe Ia (the current record holder is at z = 4; Cooke et al. 2012). Nevertheless, there is still no consensus on what powers SLSNe, which can be a hurdle in using them as tools.

Important clues to the nature of SLSNe can be derived from the environments they are found in, which are very different from those of regular SNe. Several studies have shown that SLSNe I show a strong preference for dwarf galaxies (< 10^9 $M_\odot$), which have low metallicities and are often extremely star-forming and interacting (Figure 3). One of the most comprehensive studies has been produced by the SUSHIES team (Leloudas et al.

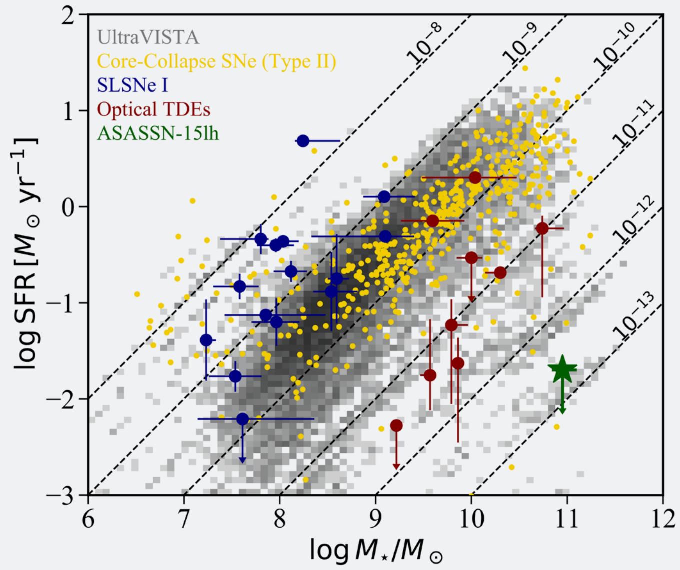

***Figure 3:** The host galaxy properties for different types of transients can provide important clues for their nature. The host galaxies of typical core-collapse SNe (Type II) are consistent with the main sequence of star forming galaxies in star formation rate versus stellar mass (taken from the UltraVISTA survey for z < 0.4). Dashed lines mark equal specific star formation rate. SLSNe I are typically found in starbursting (dwarf) galaxies pointing to massive progenitors. In the contrary, TDEs occur in more passive galaxies below the main sequence. There are only deep limits for the star formation at the location of the extreme event ASASSN-15lh (modified from Leloudas et al. 2016).*

2015, Schulze et al. 2018) where it is suggested that SLSNe represent the first explosions after a starbursting episode, indicating very high progenitor masses.

Except the mysterious SLSNe I, there also exist their H-rich siblings: SLSNe II. These have spectra dominated by narrow Balmer lines indicating that they are powered by circumstellar interaction with H-rich circumstellar material. It is therefore considered that they are "just" the high-luminosity tail of their low-luminosity cousins, SNe IIn. For this reason, they have perhaps attracted less attention than SLSNe I. However, future systematic studies might shed more light to these exciting phenomena.

The faint – a diverse class of objects

We usually classify as "faint", transients less luminous than M = –16 mag. These include both the faint tail of the ordinary core-collapse supernova distribution, especially of Type II, but also phenomena that can be of fundamentally different nature. Sometimes, these transients are called "gap transients" as they are found in the luminosity "gap" between supernovae and regular novae (Figure 2).

Particularly interesting is a class of transients that have been termed "Ca-rich", due to the strong Ca lines in their nebular spectra. These objects have typical luminosities of M = –16 mag, short rise times of 10 days, and spectra reminiscent to those of Type Ib/Ic supernovae around peak. They enter the nebular phase (i.e. their ejecta become optically thin) unusually early (typically at 30 days versus > 100 days for normal supernovae). The first object to be noticed with these unusual properties was SN 2005E (Perets et al. 2010), but it quickly became apparent that this is a distinct class with more members (Kasliwal et al. 2012). What is especially striking about these transients is the large offsets that they are found from their host galaxies (often > 20-30 kpc)! In fact, these offsets sometimes make it hard to even associate them with a specific galaxy as they can appear "hostless". At the same time, for most Ca-rich transients, there is no evidence for any underlying star formation. These last two properties immediately indicate that the progenitors of these explosions must be related to an old stellar population, making it very unlikely that they can be related to the collapse of a massive star. The favored progenitor scenario therefore involves a binary system of white dwarfs which was likely ejected from the host (or a globular cluster) and had sufficient time (many Gyr) to travel to a remote location. The exact explosion mechanism is however debated although different suggestions have been proposed such as He shell detonations on the surface of the white dwarfs. De et al. (2020) estimate that the true rate of these events is about 15% of regular Type Ia supernovae (which are also thermonuclear explosions of white dwarfs).

Other transients that are found in the gap between novae and supernovae are the eruptions of Luminous Blue Variable (LBV) stars, such as eta Carinae, a class of intermediate luminosity red transients (ILRTs), which might be related to weak electron-capture supernovae, and luminous red novae (LRNe) that may be associated with the results of stellar mergers and the ejection of a common envelope (see Pastorello & Fraser 2019 for a review of these classes). Finally, in the faint regime, we also find the famous kilonova AT 2017gfo, which was associated with the source of gravitational waves GW170817 (Abott et al. 2017). A kilonova occurs when two neutron stars merge and produce radioactive material of heavy isotopes. Due to the small ejected masses (M_{ej} ~ 0.04 $M_\odot$) and high opacities the resulting transient is faint (the name kilonova actually means that it is 1000 times brighter than a nova!) and very red. Neutron star mergers and kilonovae might be responsible for the production of the heaviest elements in the Universe, including gold (although the presence of gold has *not* been confirmed in AT 2017gfo).

The fast – Rapidly evolving transients

The majority of transients in the transient phase space evolve with characteristic time scales > 2 weeks (Figure 2). For example, the rise time of Type Ia SNe is 15-20 days, while SNe II have characteristic plateaus of 100 days. In fact, most searches in the past were tailored to discover such supernovae (by employing e.g. a typical cadence of 4 days), while faster events could be easily missed. In addition, even if such a fast transient was discovered, an equally fast reaction was required to follow it up (e.g. by means of spectroscopy) making its study operationally difficult. Nevertheless, modern surveys now possess the necessary infrastructure and motivation to explore this region of the phase space and it has been possible to uncover a population of rapidly evolving transients (RETs).

More than 100 of these objects have now been discovered in archival searches by the PS1 survey (Drout et al. 2014) and the DES survey (Pursiainen et al. 2018). They have typical rise times between 1-10 days, decline rates that can be as fast as 0.4 mag / day (5 times faster than a Type Ia SN), their spectra (when available) are typically featureless, and they have initial blue colors that can be modelled by a black body and that get redder with time. For this reason, they are often also encountered under different names, such as Fast Blue Optical Transients (FBOTs). In fact, there is no broad consensus on how exactly to define a specific class of rapid transients, or even if one single class can be defined at all. RETs span a very large range of absolute luminosities (–15 > M > –22 mag), which means that they are likely a heterogeneous class, as it would be very difficult for one single mechanism to give rise to this diversity. In any case, under RETs we do not include here a number of other transients discussed previously that could fit some of the criteria presented above, such as Ca-rich transients or kilonovae. Once we correct for the fact that we are intrinsically biased against finding these events, it turns out that RETs are relatively rare, but not that rare: their true rate can be as high as 30% of Type Ib/Ic supernovae. They are typically found in star-forming galaxies, so likely related to massive stars, but not as extreme as SLSNe (Wiseman et al. 2020).

A number of physical mechanisms has been proposed for RETs. What is certain is that canonical radioactive decay of Ni^{56} cannot explain these events as it cannot reproduce their light curves. Alternative scenaria that have been proposed include shock breakout in a stellar wind or shock-cooling emission from extended stellar envelopes. Perhaps the most famous RET is AT 2018cow (also known as "the cow"!) as it is the most nearby RET that has been discovered (z = 0.014) and it has been followed extensively, producing a number of studies (e.g. Prentice et al. 2018, Margutti et al. 2019). This event had a rise time of 2.5 days and reached a luminosity of M = –20 mag, bringing it easily in the SLSN regime, before declining rapidly at a rate of 0.4 mag / day! It was also detected in the radio and the X-rays, but despite the exquisite quality of data, no consensus has been reached on its origins with suggestions spanning phenomena as different as a central engine or a tidal disruption by an intermediate mass black hole! In the recent years, a few more transients that could fit the RET description have been discovered and studied, in particular by the Zwicky Transient Facility (ZTF). A study of 12 nearby events (albeit not the most extreme RETs, all with durations > 5 days) found in a systematic search, showed that they all evolved spectroscopically to generally ordinary supernova types (Types II, IIb, Ibn, IIn, Ic-BL; Perley et al. 2020). It is still not clear, however, whether these nearby events belong to the same population as the RETs from PS1 and DES.

Tidal disruptions of stars

Tidal disruption events (TDEs) mark the gravitational disruption of stars that pass close enough to super-massive black holes and get torn apart by their gravitational field. Half of the mass of the disrupted star becomes unbound but the other half is bound in highly eccentrical orbits and it eventually forms an accretion disc around the black hole where it gets heated before getting accreted onto the black hole. This event manifests with a transient burst of radiation. The existence of TDEs was theoretically predicted many years ago (Rees 1988) and some first candidates were discovered later in the X-rays and shorter wavelengths. But it was again thanks to the advent of wide-field optical surveys that this field has gained a new momentum, as there is now a well-established class of optically-discovered TDE candidates (van Velzen et al. 2020), numbering more than 40 events discovered after 2010. The location of these events is consistent with the nucleus of their host galaxy, where the a supermassive black hole is normally expected to be, and they show little temperature (colour) evolution, unlike supernovae that normally cool down with time. Spectroscopically, optical TDEs are dominated by H and/or He broad emission lines at differ-

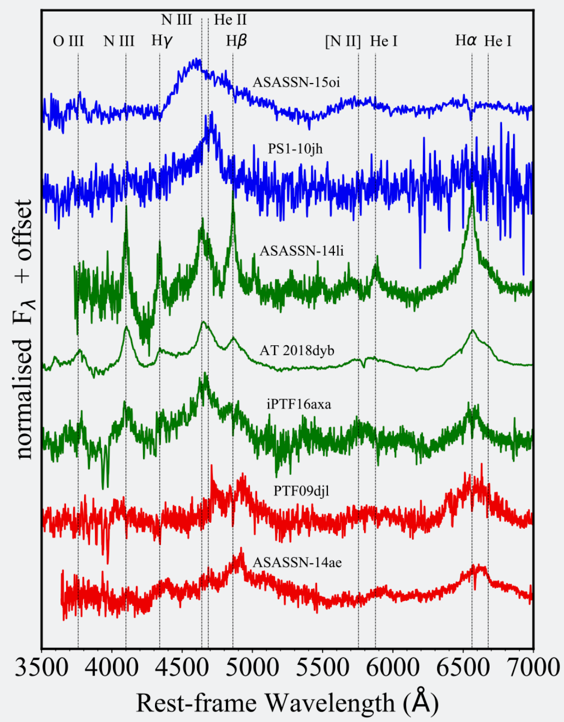

Figure 4: *Spectra of optical TDEs showing a continuum of spectral properties. In blue, we show example TDEs that show lines of He II without any evidence for H. In green, we show TDEs with both He II, H and Bowen fluorescence lines (N III, O III). Finally, the TDEs coloured in red are dominated by Balmer lines, while He is absent (modified from Leloudas et al. 2019).*

ent strengths and ratios (Arcavi et al. 2014). In addition, it has now become apparent that a significant fraction of TDEs show Bowen fluorescence lines (Figure 4).

Similar to other accretion-related phenomena (such as X-ray binaries, cataclysmic variables and AGNs) TDEs are prime laboratories for studying black holes at different scales of gravity and time. The vast majority of supermassive black holes in the Universe are invisible to us (with the exception of those in very nearby or active galaxies) and they can only be probed when they are momentarily "lit up" by a TDE. For this reason, it is imperative to understand the physics behind TDEs and their emission mechanisms. Despite the progress achieved, there are many open questions. Perhaps the biggest puzzle is the very existence of optical TDEs itself: if powered by accretion, then the predicted temperatures of TDEs should peak at 10^5-10^6 °K and the radiation should come out in the X-rays. So how is it possible to even find TDEs that emit in the optical/UV, in most cases without any X-rays at all, and with typical black-body temperatures of 10^4 °K? One possible explanation is that the accretion region is surrounded by an optically thick photosphere, likely originating in material from the disrupted star itself, which reprocesses the radiation and re-emits it in longer wavelengths (Guillochon et al. 2014). An alternative explanation is that the observed energy may be liberated by collisions between debris streams during the formation of the accretion disc, i.e. before the actual accretion (Piran et al. 2015). The discovery of Bowen fluorescence lines seems to favour the hidden accretion scenario as a strong source of X-ray/EUV photons able to excite the He II Lyα line is required (Leloudas et al. 2019).

Truly unique events

Except the "old" traditional transient classes, such as ordinary Type Ia and core-collapse supernovae, which number many thousand members, and the more recent transient classes, such as the ones described above, numbering hundreds (e.g. SLSNe, RETs) or tens (e.g. Ca-rich, TDEs) of objects, occasionally, truly unique events appear that are dissimilar to anything we have witnessed before. Such transients defy a categorical classification and puzzle us with their peculiar nature. Although intrinsically rare, due to the large numbers of transients found today, it is not infrequent to find a few peculiar cases. It is not the purpose of this review to make an extensive list of all unique and peculiar transients. The purpose is rather to show that the Universe does not cease to surprise us with exotic phenomena! I will here highlight two such transients that have attracted significant attention.

ASASSN-15lh reached an immense luminosity of M = –23.5 mag being at least twice as bright as any supernova discovered before. Some initial spectroscopic similarity with SLSNe I, led Dong et al. (2015) to classify ASASSN-15lh as the brightest SN ever recorded, even if truly extreme models would have to be invoked, pushing even models for SLSNe to their limit. An alternative explanation (Leloudas et al. 2016) is that ASASSN-15lh was an extreme TDE, consistent with the passive nature of its host galaxy (Figure 3) and its location exactly in the nucleus. The temperature evolution is also more consistent with a TDE. The problem with this interpretation is that the mass of the supermassive black hole of ASASSN-15lh is too large (> 10^8 Msun) to produce an observable TDE. For so massive black holes, the tidal radius lies inside the event horizon and therefore no signal from any stellar disruption should be expected! The solution proposed for this is that the black hole is rapidly spinning which would bring the event horizon closer to the singularity allowing for the disruption to take place outside it. At the same time, the assumption that the black hole is spinning rapidly, elegantly explains the energetics of ASASSN-15lh.

Another true "weirdo" was the supernova iPTF14hls (Arcavi et al 2017). This was an event that was spectroscopically identical to normal Type II supernovae but its light curve had a duration of 600 days (versus 100 days), demonstrating at least 5 episodes of rebrightening during this time! The exact nature of this event remains debated as no explanation is entirely satisfactory. The most favoured scenario involves the ejection of multiple shells (possibly consistent with an archival eruption observed in 1954) via the pulsational pair instability mechanism, but even this cannot explain all the observables and many other alternatives have been proposed in the literature.

Challenges and future outlook

The rapid progress in transient astrophysics has demonstrated the richness of the transient sky and has revealed a wealth of phenomena that await to be elucidated. Their impact is important in many domains, extending beyond astrophysics. Who can argue that the discovery of the kilonova associated with a gravitational wave was one of the biggest scientific breakthroughs of the last decade? But together with opportunity, come great challenges. The large numbers of transients discovered today require a change in the way we do transient astronomy.

One of the biggest challenges presented together with the advent of wide-field cameras is the lack of corresponding spectroscopic time. In plain words, this means that we do not have the resources to follow-up and study all these transients that we discover. The transient name server (TNS[1]), a facility that was introduced exactly in order to manage and bookkeep transient discoveries, reports that in 2020 there were 21664 transients reported by different surveys. Out of these, only 2091 (i.e. less than 10%) have a spectroscopic classification! This means that for all the rest we do not know their nature. This trend is only getting worse with time, as the number of transient discoveries steadily increases (Figure 1), and is expected to culminate in the near future, after the employment of the Legacy Survey of Space and Time (LSST) at the Vera C. Rubin Observatory. LSST is expected to survey the entire southern sky at a depth of 24 mag, and discover many hundreds of thousands of transients! To fully exploit this potential, a large amount of telescope follow-up time would be necessary, with spectroscopy in particular. This would require a large number of dedicated robotic telescopes but even in the most optimistic scenario this is not going to suffice.

1. https://www.wis-tns.org/

Therefore, together with accelerating our efforts to optimally exploit already existing as well as developing new facilities, we will need to reconsider our methodologies. We are entering the era of big datasets and the analysis will need to be targeted towards large samples of events (even for what are today considered to be rare transients) rather than producing studies on individual events. For example, TDEs will be discovered in large numbers and over a large redshift range and they can be used to map the formation and mass evolution of supermassive black holes across cosmic time. The analysis of such large datasets borders computer science and the future astronomers will need to be equipped with knowledge of advanced analysis tools, such as machine learning. Furthermore, rather than following-up just any supernova (which is already impossible today) it is imperative to perform a strict selection of the objects that are most interesting to answer individual research questions. For example, a scientist aiming to study the acceleration of the Universe with SLSNe at high redshift, will first need to develop a method to find these objects and efficiently select them as real needles in the haystack of transients. The same is true for many other kinds of transients many of which present different operational challenges. For instance, the community interest has already progressively shifted towards finding very young transients, i.e. just a few hours from explosion, which allows to constrain important physical parameters of the progenitor stars, while finding the same transient a few days later is too late. The transient revolution is just maturing. Exciting times lie ahead!

Acknowledgements

I thank Miika Pursiainen for providing a modified version of Figure 1 from his PhD thesis and for providing comments on the manuscript.

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The above web server contains information, both in greek and english, about the Hellenic Astronomical Society (Hel.A.S.), the major organization of professional astronomers in Greece. The Society was established in 1993, it has more than 250 members, and it follows the usual structure of most modern scientific societies. The web pages provide information and pointers to astronomy related material, useful to both professional and amateur astronomers in Greece. It contains a directory of all members of the Society, as well as an archive of all material published by the Society, including electronic newsletters, past issues of "Hipparchos", and proceedings of Conferences of Hel.A.S. The server is currently hosted by the University of Thessaloniki.

Predicting Solar Energetic Particle (SEP) events: current status and future perspectives

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I. Abstract:

Space Weather effects of Solar Energetic Particle (SEP) events range from the direct radiation hazard that those impose to crews and equipment primarily in the interplanetary space to ramifications within the Earth's magnetosphere and atmosphere. Hence, SEP events are of particular importance for the near future planned manned missions to the Moon and Mars, as well as, for the un-obstacle daily living. In this review, we present key findings that have been utilized and/or explored by the scientific community over the last decades in order to establish prediction schemes of SEP events. We first discuss how the parameters of the parent solar events (i.e. solar flares and coronal mass ejections - CMEs) are related to the probability of occurrence and critical characteristics (i.e. peak proton flux, fluence) of SEP events in the near-Earth environment and beyond. Next, we review modeling efforts of SEP events that are geared towards operational prediction, particularly focusing on transport effects and multi-spacecraft observations. We, further, explore the applicability of higher order multivariate, machine learning and artificial intelligence methods and highlight the particular value and limitations of such advances. Finally, the most recent current operational approaches in the prediction of SEP events, together with future challenges that need to be addressed by the scientific community are put forth and discussed.

Keywords: Sun: particle emission • Sun: solar flares • Sun: coronal mass ejections-CMEs • solar-terrestrial relations • space weather

II. Introduction

Solar energetic particle (SEP) events are recorded as clear enhancements above the background response of detectors orbiting within the near-Earth, the inner heliosphere and the interplanetary (IP) space (Reames, 2021). These particle fluxes are consisted of protons, electrons and heavier ions and their energy spans over many orders of magnitude, from a few keV to hundreds of MeV extending even to the GeV range, in some cases (see e.g. Anastasiadis et al., 2019). SEP events last from a few hours to several days and can adversely affect space and ground-based systems.

Space Weather effects associated with SEP events include communication and navigation systems interference, failures in spacecraft electronics, space power systems damages (Iucci et al., 2005), enhanced radiation risk for manned space missions (Cucinotta et al., 2002), and aircrews in commercial flights (see e.g. Schwadron et al., 2017). Based on the new planned manned missions like Artemis[1] and their vital role in today's modern technological dependent society there is a clear need for the development of a scheme which will provide advanced warning of SEP events and their expected characteristics. In particular, it is of paramount importance to predict when and where an SEP event will (or will not) take place, what would the maximum peak intensity of this event be and what the duration and ultimately the time profile of the SEP event will be. All these information are difficult to elucidate due to the inherent complexity of the subject, the variability of SEP events and the current gap of knowledge.

After of more than 50 years of space observations we can conclude that SEPs are accelerated by solar flares and coronal mass ejections (CMEs) (Reames, 1999; 2021; Papaioannou et al., 2016; Vlahos et al., 2019). SEP events are classified as impulsive and gradual, with the former being of short duration (≤1 day), lower intensity and numerous – presumably associated to flares; while the latter being of longer duration (lasting up to several days), relatively rare and covering many orders of magnitude in their achieved intensity – presumably associated to CMEs (see e.g. Reames, 1999; 2021). The transport of SEPs is governed by the propagating conditions met at the IP space (Kahler, Burkepile & Reames, 1999, Kahler and Vourlidas, 2014a, Lario and Karlitz, 2014); the presence of seed population (Tylka et al., 2005; Desai et al., 2006) and the interaction of multiple CMEs (Kahler and Vourlidas, 2014b). Thereby, complex environment and physical processes dominate the origin, acceleration, injection and transport of particles in the IP space, masking the connection between the properties of SEP events and their progenitors at or near the Sun.

Moreover, the temporal scale of SEP prediction further adds to the difficulty of the prediction efforts. However, based on a few decades of available measurements, linkages between parent solar and SEP events have been revealed and as a consequence several dependencies have been identified (see e.g. Klein and Dalla, 2017). Hence, the wealth of statistical and modeling studies underpins the science related to the acceleration of the SEPs and provides outstanding scientific understanding which in turn is required in order to assess and predict SEP events.

III. Key dependencies

It has been established that both fast and halo CMEs form favorable conditions for the acceleration of particles that will result in SEP events since

1. https://www.nasa.gov/specials/artemis/

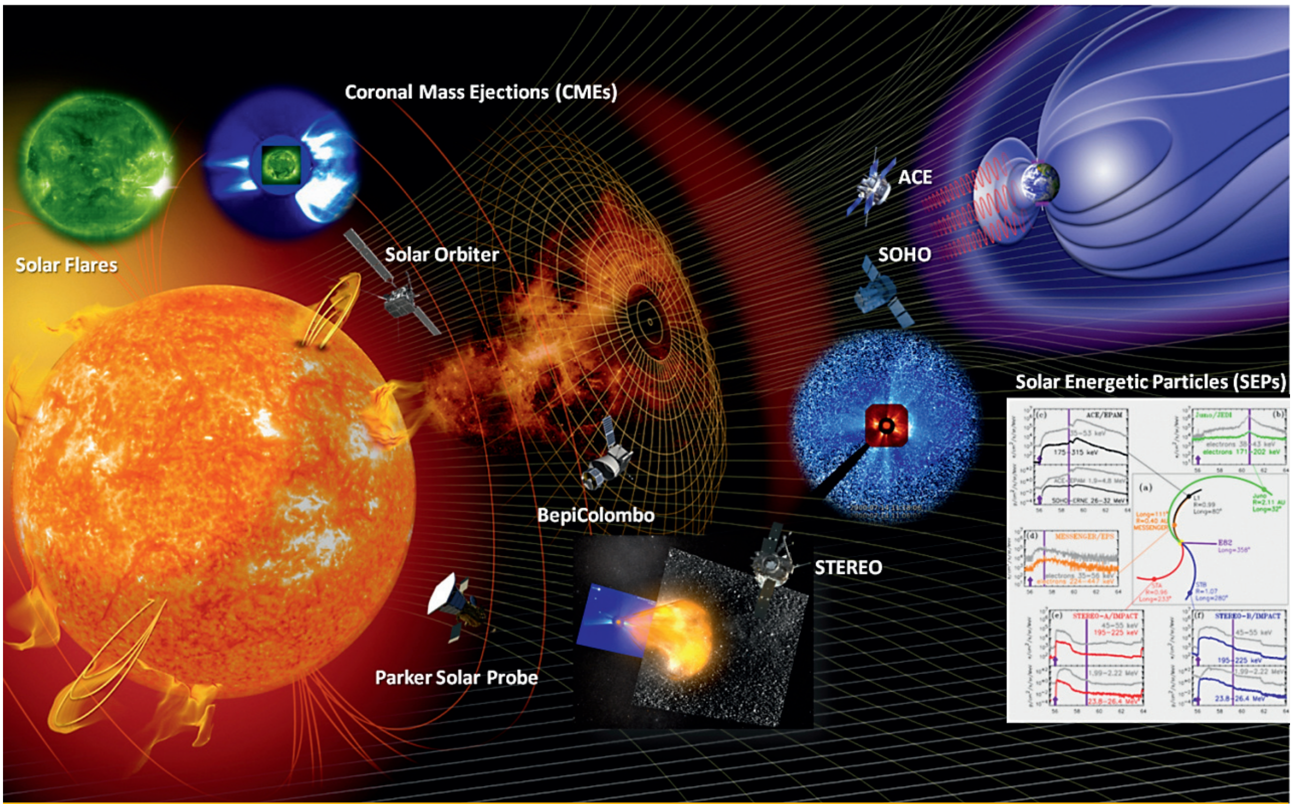

Figure 1: *A schematics of geospace and the inner heliosphere, for context. A solar flare observed by SDO and a CME recorded by LASCO are included in the figure to underline the parent solar events of SEPs. Missions presented span from radial distances very close to the Sun (i.e. the current missions of Solar Orbiter, Parker Solar Probe & BepiColombo) to 1 AU (STEREO) and to L1 watchdogs (SOHO & ACE). A mutli-spacecraft SEP event denotes the longitudinal evolution of particles in the inner heliopshere (adapted and combined from images available by SOHO, ACE, LASCO, SDO, PSP, SolO, STEREO and the Lario et al., 2013 paper).*

these are a prerequisite for the establishment of a shock, driven by the corresponding CME event. Hence, a fairly reasonable correlation between the peak of the SEP flux and the speed of the CME has been identified (see e.g. Kahler 2001; Cane et al., 2010; Papaioannou et al., 2016). This is expected since particle acceleration models at CME driven shocks point to the dependence of the acceleration rate on the speed of the shock travelling in the upstream region (see Lee et al., 2012; Kouloumvakos et al., 2019). Nonetheless, such a dependency in not definite since many different factors can affect the SEP intensity (see e.g. Lario and Kaleritz, 2014, Richardson, Mays and Thompson, 2018), including the importance of shock geometry and seed particle populations for shock acceleration (see Tylka et al., 2005), as well as, the usage of a crude proxy as the projected speed of the CME which's value varies with respect to the catalogue employed each time (Richardson et al., 2015).

In addition, the SEP occurrence depends on the heliolongitude of the parent flare (e.g. Belov et al. 2005) pointing to the magnetic connection that needs to be established, so that particles shall be routed to the observer site. In other words, western locations on the solar disk have a higher potential to result in an SEP event at (e.g.) Earth, due to the curvature of the Arhemidean spiral IMF (Desai and Giacalone, 2016). Yet, the legacy of the Solar Terrestrial Relations Observatory (STEREO) mission has shown that wide-spread SEP events are detected at locations broadly separated in longitude (see e.g. Papaioannou et al., 2014; Richardson et al., 2014) from the site of the parent flare and particles spread even over almost 360° (Gomez-Herrero et al., 2015). For these multi-spacecraft SEP events, CME-driven shocks were the apparent explanation (Rouillard et al., 2011; Lario et al., 2013), pointing to gradual SEPs. Nevertheless, it has been shown that even impulsive SEP events are registered over wide longitudinal separations (Wiedenbeck et al. 2013).

Finally, Garcia (1994a) showed that there is a temperature dependence that distinguishes flares associated with SEPs from flares that are not. Moreover, another category of flares are also associated to SEP event: those with progressive spectral hardening in hard X-rays that usually follow the flare's impulsive phase by significant time intervals (Kiplinger, 1995). These two types of flares overlap at the upper M-class and lower X-class flare intensities (Garcia, 1994a). Building on this observational evidence Garcia (1994b) demonstrated that the ratio *R* of the two nominal 0.05-0.4 nm and the 0.1-0.8 nm bands of GOES soft X-rays can be used in order to compute the flare plasma temperature and emission measure. The work by Garcia was recently updated for the 1998–2016 time period in which SEP events were separated based on their achieved peak flux at an integral energy of E>10 MeV, by Kahler and Ling (2018). The authors found that flares that led to small SEP events (peak flux < 10 pfu) were not well separated from the flares that led to non-SEPs, in contrast to typical NOAA SEP events, whereas large

(≥300 pfu) SEP events originating from flares located in the western solar hemisphere are much better separated from non-SEP flares.

IV. Predicting SEP events

a. Proxies
| *cause and effect* relations

Such (and other) key observational dependencies, listed in Section III, have been utilized as indicators/classifiers for the development and the implementation of concepts that offer forewarning of SEP events. However, the prediction of SEP events is based on different time scales directly driven by the input employed. Therefore there are *long-term* and the *short term* predictions with the former termed as *forecasts* and the latter as *nowcasts* (see details and definitions in Anastasiadis et al., 2019). The majority of the operational concepts today offer *nowcasts*, while intensive efforts of the scientific community seek to find a solution to the delivery of accurate forecasts, well ahead of time (Falconer et al., 2011). Such efforts, exploiting flare or CME characteristics, have been proposed by the scientific community. In particular:

Solar flares

Initially (in the 70's and 80's), and up until today, flare characteristics were the main (and only) contributor to such SEP prediction concepts. This is because flares: (a) were routinely delivered by GOES patrol measurements since 1976 – long before the SOHO era in 1997 that made CME identifications possible in the space era; (b) are available at every minute (i.e. 1-min or 5-min) and thus perfectly suit operations and (c) a

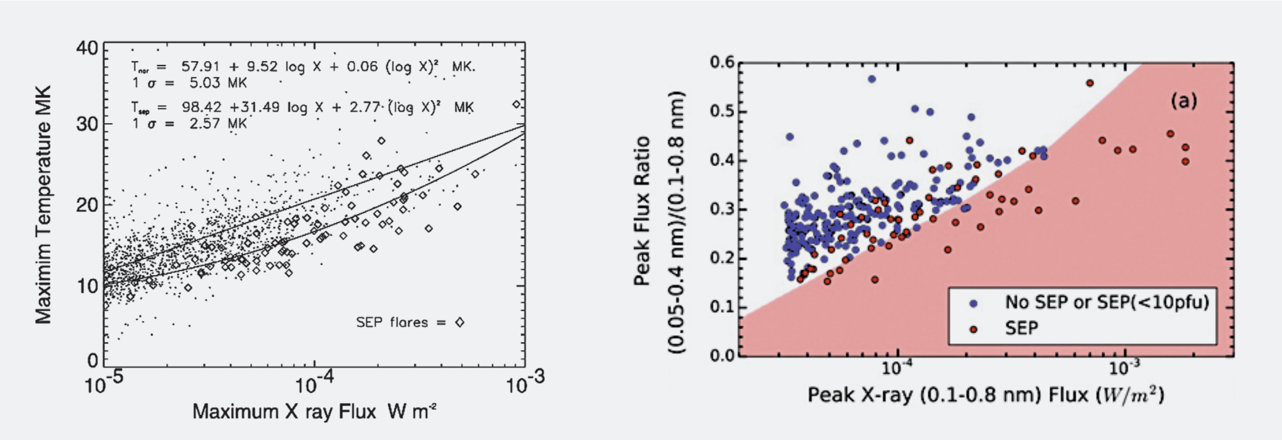

Figure 2: *The maximum temperature (in MK) versus the maximum SXR peak flux (in W/m²). Flares associated to SEP events are depicted as diamonds whereas flares not associated to SEP events as dots (from Garcia 1994a) (left hand side). The Peak Flux Ratio (R) as a function of maximum SXR peak flux (in W/m²) for flares associated (red dots) and not associated or achieving a peak proton flux < 10 pfu (blue dots) to SEP events (adapted from Kahler and Ling, 2018).*

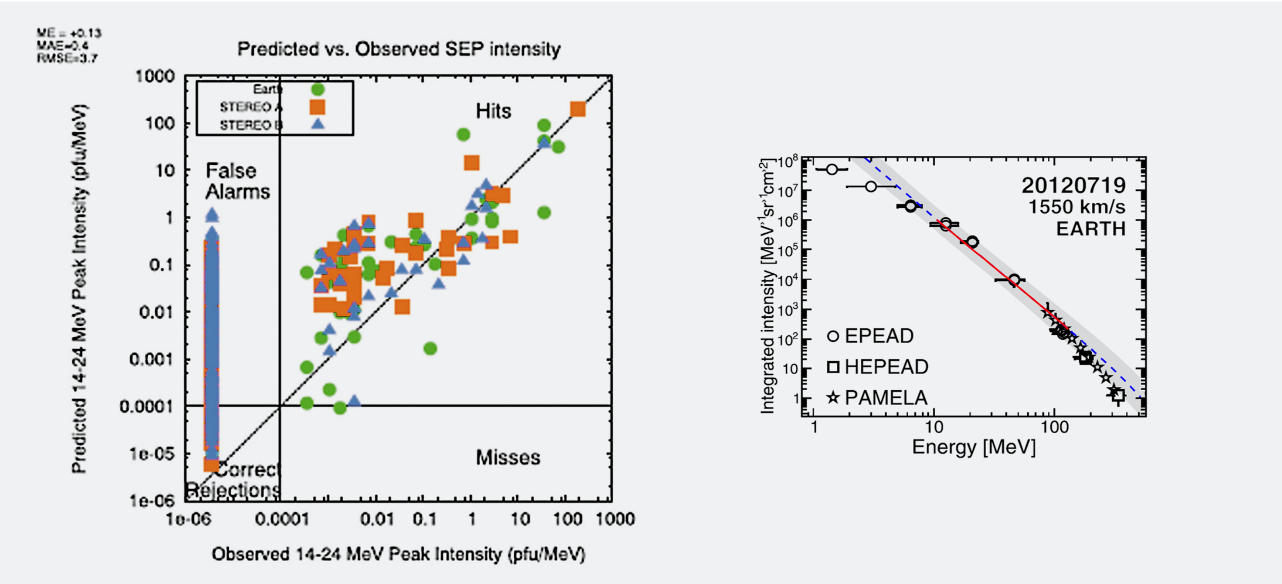

Figure 3: *Panel on the left hand side: SEPSTER Predicted versus Observed peak fluxes at E=14-24 MeV. Each color and shape corresponds to a different observer (i.e. Earth, STA, STB). The plot serves as a contingency table since it shows the false alarms, hits, misses and correct rejections based on a threshold of 0.0001 pfu/MeV which is approximately the instrument's threshold (from Richardson, Lays and Thompson, 2018). (Panel on the right hand side) The predicted SEP spectra for the event on 19/07/2012. Red lines are the actual predicted spectra between 10-130 MeV; the dashed-blue lines are the extrapolations to lower/higher energies. The gray band denotes the one-σ uncertainty associated with the model prediction. The experimental data for comparison include GOES (EPEAD and HEPEAD) as well as the high-energy observations of the PAMELA experiment, marked by empty stars (from Bruno and Richardson, 2021).*

wealth of observational evidence (see Section III) pointed to their close connection to the underlying acceleration, injection and propagation of SEPs. That said, two of the very first *nowcasting* systems were put forth by the National Oceanic Atmospheric Administration (NOAA) and the Air Force Research Laboratory (AFRL), namely PROTONS (Balch, 2008) and the Proton Prediction System (PPS) (Kahler et al., 2017). Adding to these, concepts that use lag-correlation between SXR and particle (differential and/or integral) fluxes near Earth have been proposed under the UMASEP scheme which was initially trained for E>10 MeV (Nunez, 2011) and later extended to higher energies (E>100 MeV and E>500 MeV) (Nunez, 2015).

CMEs

Although gradual SEP events have direct Space Weather relevance (see Section I), the fact that: (a) routinely obtained data onboard SOHO by LASCO were made available only since 1997 and (b) the telemetry of the data imposes a ~6 hour time delay between data reception and data retrieval the usage of CME identifications has not been fully explored by the scientific community. Nonetheless, recently, simple 2D probability functions for the probability of SEP occurrence based on the width and the speed of CMEs, as well as, linear regressions of the SEP peak flux to the CME speed were derived (Papaioannou et al., 2018) which were then integrated into the Forecasting Solar Particle Events and Flares (FORSPEF) tool (Anastasiadis et al., 2017). Another simple formula, i.e. SEPSTER (SEP predictions based on STEREO observations), was put forth (i.e. Richardson et al., 2014) showing promise in the prediction of the SEP peak flux at 14-24 MeV, at different vantage points within the heliosphere (i.e. Earth, STEREO-A & B) utilizing the CME speed and the connection angle Φ of the observer (Richardson, Lays and Thompson, 2018). This concept was further expanded in order to provide the expected proton peak flux particle spectra ranging from 10-130 MeV at 1 AU (Bruno and Richardson, 2021).

In-situ particles

Apart from the signatures of the parent solar eruptive events of SEP events (flares, CMEs), Posner (2007) demonstrated that near relativistic electron fluxes can be successfully used for the nowcasting of 30–50 MeV protons. The Relativistic Electron Alert System for Exploration (REleASE) concept is based on a matrix that maps the registered electron intensity to the expected intensity of the protons and thus provides a deterministic nowcasting of the expected proton flux at each moment of time. Due to the fact that it only relies on in-situ electron data (and not parent solar eruptive events) REleASE can be used also in the absent of solar signatures (i.e. backsided flares).

b. Modeling | *physical mechanisms*

A mounting body of work has been devoted to understand the origins, acceleration, injection, transport, and properties of SEPs – mainly at 1 AU. These constitute primary open issues that have not yet been resolved. Namely, (1) **SEP origin;** Observations of rare solar wind (SW) elements in SEP events has provided compelling evidence that CME-driven IP shocks accelerate material preferentially out of a suprathermal pool (Desai et al. 2006). This pool comprises contributions from heated solar wind, coronal material, and remnants of solar transient events, among others. Quantifying the relative contributions of seed population to SEPs is critical to understanding the event-to-event variability. (2) **SEP acceleration**; different particle acceleration processes occur at shock waves, the shock-drift mechanism at quasi-perpendicular shocks and the diffusive shock acceleration (DSA) process at quasi-parallel and oblique shocks are primary candidates together with shock surfing acceleration (e.g Vainio & Afanasiev, 2018). (3) **SEP emission**; the emission of particles at the shock depends on the conditions around the shock; i.e. the presence of a turbulent wavy region upstream of the shock; (4) **SEP transport**; Scattering in the IP medium plays a critical role in determining SEP observations. Studies showed evidence of particle scattering by Alfvén waves generated by streaming protons accelerated at shocks, indicating that IP scattering is sometimes dominated by a dynamic wave spectrum rather than a universal background one (e.g., Tylka et al. 2005). Rigidity-dependent scattering of particles has been used in order to explain SEP particle intensity temporal profiles and spectral variability (Desai and Giacalone, 2016). However, it becomes apparent that in order to improve the quality of predicted SEP properties it is essential to introduce physical mechanisms into the prediction chain.

c. Multivariate statistical & machine learning methods

With the current availability of large datasets that continue to grow (e.g. GOES SXR and particle data; SOHO/LASCO), and given the complexity of underpinning the relation of the parent

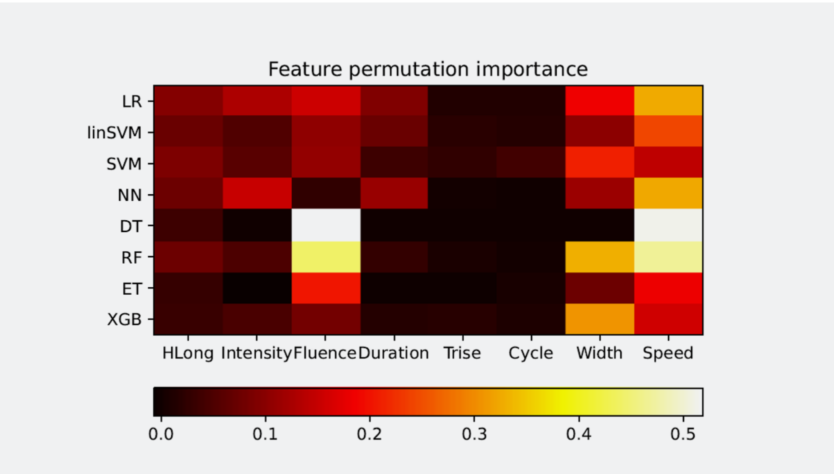

Figure 4: *Colormap of feature permutation importance scores. The x-axis depicts the eight (8) features that were investigated while the y-axis presents the eight (8) ML models that were applied in the study. The colorbar overlays the achieved permutation importance score for each case (i.e. model & feature). CEM speed, width and SXR Fluence stand out in several of the employed models (from Lavasa et al., 2021)*

solar events to SEPs and the different variables that give rise to their characteristics, predictive efforts have focused on higher dimensional order correlations and have increasingly been turning to multivariate statistical and machine learning (ML) methods (see Camporeale, 2019 for a review). Such complex algorithms have the advantage of resolving problems, which cannot be easily approached by more traditional mathematical and algorithmic tools. For example, time series analysis of SXRs and protons recorded by GOES were used to develop successful decision tree (DT) models in order to *nowcast* SEPs at high energies (i.e. E>100 MeV) (Boubrahimi et al., 2017). These efforts were preceded by Winter and Ledbetter (2015) who applied a Principal Component Analysis (PCA) for SEP prediction. Most recently, Lavasa et al., (2021) performed a thorough analysis and applied a set of different techniques including logistic regression (LR), support vector machines (SVM), neural networks (NN), random forests (RF), decision trees (DTs), extremely randomized trees (XT) and extreme gradient boosting (XGB), further evaluating the importance of each feature employed and thus it's usage in the binary (i.e. yes or no) predictability of SEPs.

V. Current status

SEP prediction poses many challenges and there is a clear need for integrated SEP event *nowcasting* systems that will make use of the state-of-the-art implementations. This has led, for example, to the realization of *ensemble solutions*, which are designed in a way that incorporate many different models and set ups, like the novel modular Advanced Solar Particle Events Casting System (ASPECS) tool. Specifically, the ASPECS tool is a new automated modular advanced warning system of SEP events that couples data-driven concepts and physics-based models. It provides for the first time the expected SEP event time profile for a set of integral energies (E>10-; >30-; >100-; >300 MeV) in near real-time mode at 1 AU. In order to do that, ASPECS incorporates many different models in

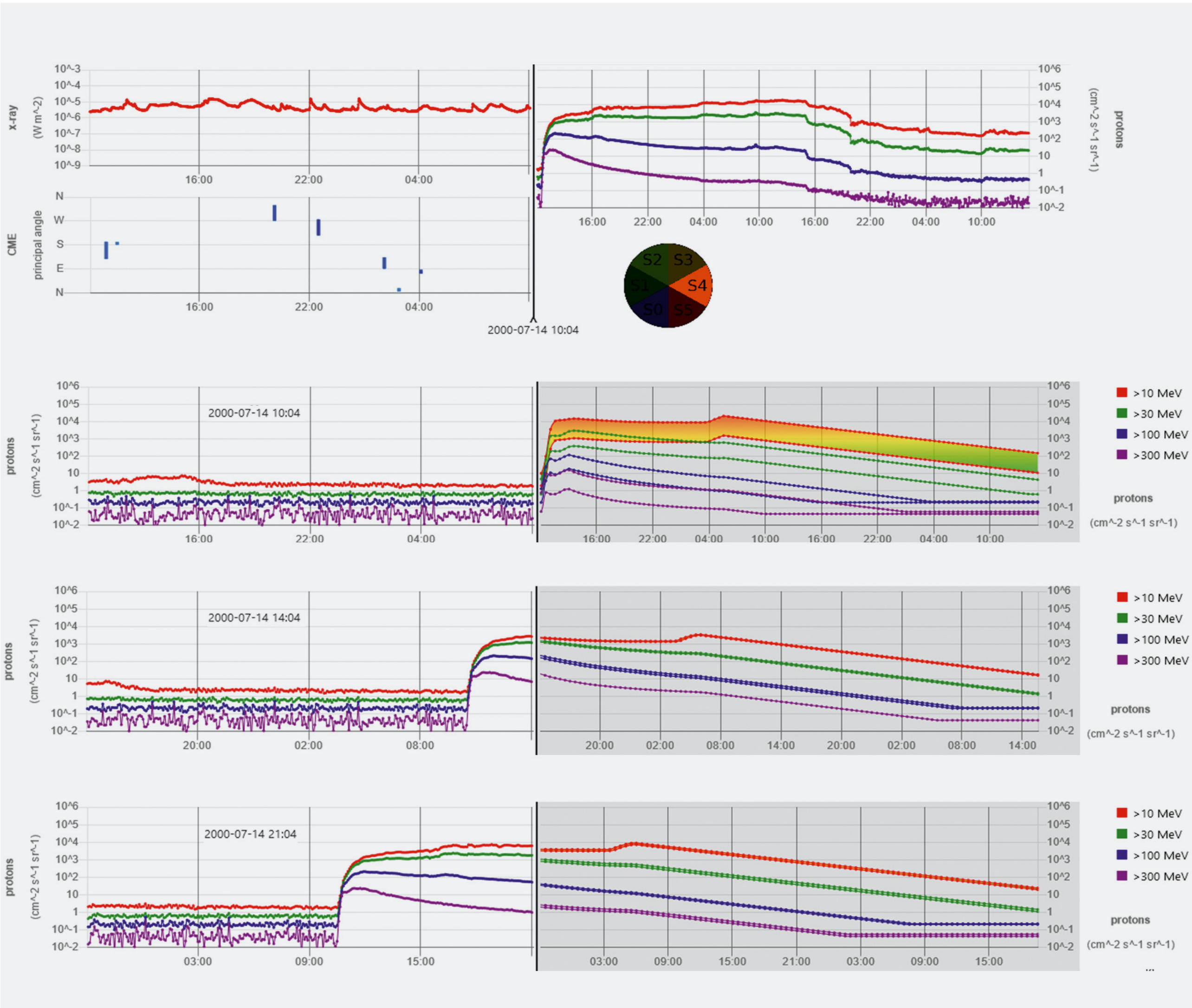

Figure 5: *A composite output from the ASPECS tool (http://phobos-srv.space.noa.gr/). From top to bottom: the SXR flux (red line) and CMEs identified by CACTus (blue vertical lines) as well as the proton peak flux for different integral energies of interest. The following 3 panels provide the prediction of the SEP time profile scaled at the 50% and 90% confidence level for each energy. The first prediction is delivered at the time of the solar flare occurrence ~50 minutes prior to the arrival of the E>10 MeV particles, then the prediction constantly evolves with time and the last two panels show the obtained SEP time profiles latter during the event.*

sequential modules that provide predictions of: (a) the SEP occurrence; (b) the expected proton peak flux at respective energies of interest spanning; (c) the expected SEP time profile using a combination of simulated time profiles based on SOLPENCO2 (Aran et al., 2006; Pomoell et al., 2015; Aran et al., 2017) and semi-analytical solutions based on a modified Weibul fitting procedure (Kalher and Ling, 2017). One of the advances of ASPECS is that it provides the SEP profile time evolution and thus it directly translates the conditions of the near Earth space into usable information during the total duration of the SEP event.

VI. Future perspectives

As noted in Anastasiadis et al., 2019: "An integrated system that mimics (different energies, thresholds, needs) terrestrial weather forecasting is the immediate future step". This is especially true and urgent. In order to accomplish this goal the scientific community needs to:

- ***Perform focused scientific work on SEP emission & transport for gradual SEP event that are directly Space Weather relevant.*** The focused transport mathematical formalism includes almost all important particle transport effects, such as particle streaming along the field line, adiabatic cooling in the expanding solar wind, pitch angle diffusion of particles, and magnetic focusing in the diverging IMF, although, the latter is typically assumed as a Parker field it still constitutes the way forward. Furthermore, enhance modeling efforts that quantify the escaping of ions at the shock on the appropriate field lines connected to the observer. The obtained SEP intensity time profiles depend on how the magnetic connection of the spacecraft (the observer) is established with the particle source; on how efficiently protons are accelerated and injected by the shock into the connecting magnetic flux tube(s), and on how the IMF irregularities modulate this population during its journey in interplanetary space. Hence, all these should be further explored.
- ***Exploit data from heritage and current missions at a range of radial distances from the Sun.*** An early milestone in our understanding of the interplanetary space was achieved back in the 70s when the twin spacecraft Helios 1 and Helios 2 explored the inner heliosphere from about 0.29 AU to 1 AU. The in situ instruments measured, among other properties, the solar wind, the heliospheric magnetic field, and energetic particles. Given the proximity of the Helios spacecraft to the Sun, and the continuous observations of SEPs at Earth, revisiting these data and utilizing the recordings at both heliocentric distances is ideally suited for stating the expected environmental context for the current ongoing missions toward the inner heliosphere (Solar Orbiter – SolO and Parker Solar Probe – PSP) and for the unfolding of the SEP propagation from 0.3 to 1 AU. This knowledge could be then used in order to provide SEP prediction across the inner heliosphere.

Human space exploration is the new frontier and its right around the corner. We need to address fundamental questions about the dominance of the Sun to the heliosphere and to be able to predict when and where an SEP event will take place. In doing so, *integrated solutions* are the way forward and currently the scientific community has the capability to make new and decisive steps towards this exciting journey!

Acknowledgements

This work was partially supported by the European Space Agency (ESA) under contract 4000120480/17/NL/LF/hh, "Solar Energetic Particle (SEP) Advanced Warning System (SAWS)"

http://tromos.space.noa.gr/aspecs/

The present work benefited from discussions held at the International Space Science Institute (ISSI, Bern, Switzerland) within the frame of the international teams: High EneRgy sOlar partIcle events analysis (HEROIC)

https://www.issibern.ch/teams/heroic/

We would further like to thank A. Vourlidas, M. K. Georgoulis, R. Vainio, A. Aran, B. Heber, M. Laurenza, S. W. Kahler, I.G. Richardson and P. Jiggens for useful discussions.

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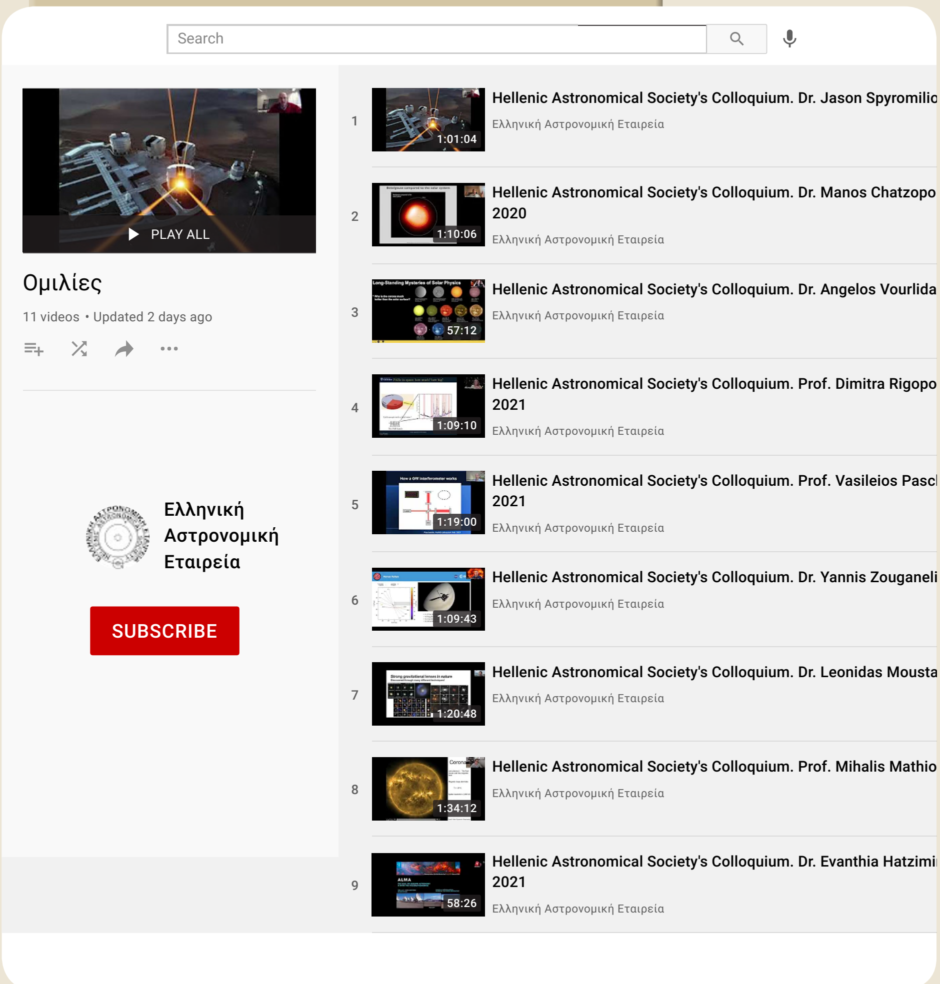

Characterising exoplanetary atmospheres: the legacy of HST/WFC3

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1. Introduction - Exoplanet demographics

The existence of planets beyond our Solar System is not a new idea. Campbell et al. (1988) cautiously claimed to have detected the first planet in orbit around γ Cephei A, while Wolszczan and Frail (1992) reported the discovery of two planets orbiting the 6.2ms pulsar PSR B1257+12. However, the first detection of a planet orbiting a main-sequence star came in 1995. It was 51Pegb, a planet with mass comparable to that of Jupiter, orbiting 0.05 AU away from its parent star (Mayor and Queloz, 1995). In 2019, M. Mayor and D. Queloz shared half of the Nobel Prize for their revolutionary discovery.

Today, the most efficient method for detecting exoplanets is the transit method. The first transiting exoplanet was discovered at the end of the previous millennium (Charbonneau et al., 2000; Henry et al., 2000), but it was only after the results of large-scale surveys from space and ground – e.g. OGLE (Udalski et al., 2002), HATNet, (Bakos et al., 2002), WASP (Pollacco et al., 2006), CoRoT, Kepler (Borucki et al., 2010), K2 (Howell et al., 2014), TESS (Ricker et al., 2014) – that we finally had a more clear picture of the planetary populations in the Galaxy. From a sample of more than 4000 confirmed exoplanets, we currently know that:

- there are at least as many planets as stars in the galaxy (Cassan et al., 2012),
- 16.5% of the main-sequence FGK stars have at least one planet between 0.8 and 1.25 Earth radii, orbiting in less than 85 days (Fressin et al., 2013),
- there is one Earth-like planet in the habitable zone for every four M type stars (Dressing and Charbonneau, 2015), and
- planets with radii below three Earth radii are the most common planets in the galaxy and they are clearly separated into two populations, the smaller and the larger ones, usually referred as super-Earths and mini-Neptunes, respectively (Fulton et al., 2017).

Current and future survey missions, such as GAIA (Perryman et al., 2001), TESS (Ricker et al., 2014), and PLATO (Rauer et al., 2014) are expected to find tens of thousands of new planets. These new populations will improve our understanding of exoplanets and will provide a huge sample of planets available for further characterisation.

For many planets we can measure the radius, the mass and the temperature. However, as it can be deduced from studying the planets within our Solar System, the bulk characteristics alone are not enough to infer the nature of a planet. The most distinct example is the comparison between Earth and Venus, two extremely different environments on two planets with almost identical masses and radii. For planets outside our Solar System, the diversity found in masses, radii and orbital parameters indicates that these distant worlds can vary dramatically. The key to understand more about these planets is to study the chemistry and the dynamics of their atmospheres.

1.1. Gas giants

Exoplanets with masses larger than ten Earth masses and radii larger than four Earth radii are expected to host a significant amount of hydrogen and helium, similarly to Jupiter, Saturn, Uranus and Neptune. Despite their simpler composition compared to rocky planets, mass-radius diagrams for the giant planets (Figure 1) do not put clear constrains on their overall internal structure.

To be noticed first from the mass-radius diagram is that most of the gaseous planets are inflated compared to models based on hydrogen composition (Bodenheimer et al., 2001; Guillot and Showman, 2002). It has been suggested that this inflation is the result of atmospheric heating through tidal orbital circularisation (Bodenheimer et al., 2001),

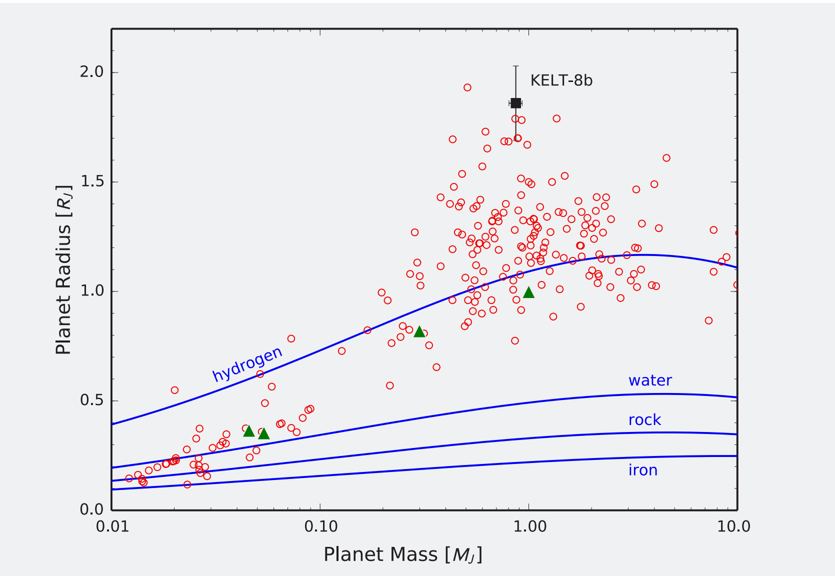

Figure 1: *Mass-radius diagram for the gas giants (Fulton et al., 2015).*

winds (Guillot and Showman, 2002), or Ohmic dissipation (Batygin and Stevenson, 2010).

Concerning the chemical composition of giant planets, due to the high temperatures of the planets detected so far (>1000 K), molecules like H_2O, CH_4, CO, CO_2 and NH_3 are expected to be in the gas phase. Determining the presence and the abundances of such molecules can answer questions like: can we explain the chemistry of the planetary atmosphere by thermal equilibrium or is non-equilibrium chemistry affecting its composition? (Venot et al., 2012), and which are the metallicity and the C/O ratio of the atmosphere? These fundamental properties are related to the formation and the evolution of the planetary systems that they belong (Matter et al., 2009) hence they provide a window to the past of these systems. Finally, another important aspect that needs to be investigated is the dynamics of the atmospheres of giant planets. The thermal structure, both horizontal and vertical, as well as atmospheric escape are important pieces of information concerning the kinetics (Showman et al., 2010) and the evolution (Lammer et al., 2003) of these planets.

1.2. Super-Earths

The term super-Earth refers to the class of planets with masses between those of the Earth and Neptune. Despite being absent in our Solar System, they are the most common planets in our Galaxy (Fulton et al., 2017). For these planets, mass and radius measurements cannot constrain their bulk composition (Figure, 2).

Apart from the assumption that super-Earths are scaled-up Earth analogues, two other explanations for their mass-radius relationship have been proposed. The first, suggests that they are “ocean-worlds”, containing a substantial amount of water (Kuchner, 2003; Leger et al., 2004), while the second, suggests that they are “mini-Neptunes”, having large rocky iron cores surrounded by a hydrogen/helium envelope (Adams et al., 2008). Current observations indicate that planets up to six Earth masses can be described by small atmospheric envelopes on top of a core with an Earth-like composition (Dressing et al., 2015), while more massive planets must host a larger, volatile-rich, envelope (Valencia et al., 2013).

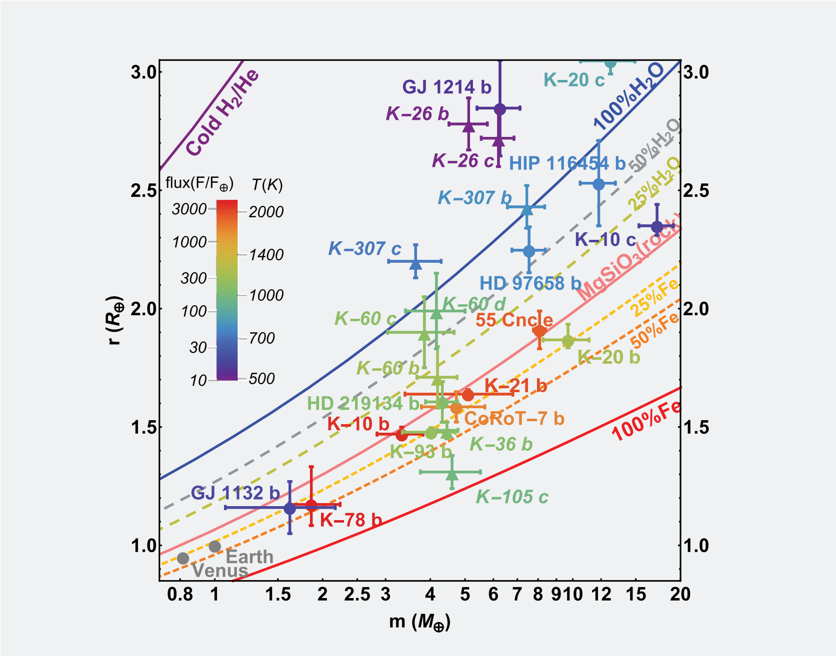

Figure 2: *Mass-radius diagram for all the currently known super-Earths with masses below 20 Earth masses, known within 20% uncertainty (Lopez-Morales et al., 2016).*

From a formation perspective, Ikoma and Hori (2012) suggested that in situ accretion of H/He rich atmospheres without disk migration is theoretically possible, but only under very specific conditions, while Ogihara et al. (2015) initial mass of the planet (Lopez and Fortney, 2013). Hansen and Zink (2015) also proposed that a super-Earth can be the result of atmospheric loss from a Neptune-mass gas giant due to tidal heating. Such a mechanism can be triggered by evolution through secular resonances, leading to atmospheric heating and Roche lobe overflow. Nevertheless, Lammer et al. (2013) provided more detailed calculations on atmospheric escape of hydrogen and helium due to XUV illumination and found that if the inflated super-Earths host H/He envelopes, they will not lose them during the remaining of their lifetimes.

An important piece of information concerning the conditions of the two classes of planets discussed above, comes from the composition of their atmospheres. More specifically, atmospheric studies can provide information on: a) the size of the gaseous envelope constraining the structure and evolution of super-Earths, and investigating the escape rates and hence the survival of the atmosphere, b) the composition of the gaseous envelope inferring the chemical and photochemical processes, the formation, and the evolution of both giants and super-Earths, and c) the thermal structure of the atmosphere probing the atmospheric dynamics, and heat redistribution.

2 Transits, Eclipses & Phase Curves

There is a number of techniques that are currently used to characterise the atmosphere of a planet and extract information on its composition and thermal structure. All these methods, which are described below, aim to separate the planetary spectroscopic signal from the stellar one.

2.1. Transit spectroscopy

During a transit event, the stellar and the planetary projected discs are overlapping, and the planet is blocking a small portion of the stellar light. Assuming that the planet is surrounded by an atmosphere, this atmosphere is also blocking a part of the stellar light. However, the amount of light blocked by the atmosphere differs at different wavelengths, depending on its composition. If we observe a transit at different wavelengths, we can measure the modulations in the apparent planetary radius and infer the existence of certain atoms, ions, molecules, hazes or clouds (Tinetti et al., 2007).

For an atmospheric envelope of

temperature T, and mean molecular weight μ, the scale height, H, is:

$$H = \frac{kT}{\mu g},$$

where k is the Boltzmann constant, and g is the gravity of the planet. The total height of the atmosphere that affects the transit depth measurements is approximately equal to five scale heights, hence the total atmospheric absorption – i.e. the maximum additional transit depth caused by a completely opaque atmosphere is:

$$A \sim 5\,\frac{2R_P H}{R_*^2},$$

where R_p and R_* are the radii of the planet and the star, respectively. This quantity is not negligible for atmospheres of low μ and high T, making hot Jupiters the best possible targets, as their atmospheres consist mainly of H/He and have a μ close to 2.3 amu. On the other hand, super-Earths are more challenging, firstly, because we do not know whether their atmospheres have a substantial amount of H/He or they are heavier, and, secondly, because they are smaller in size.

Transit spectroscopy at UV wavelengths can give us information about the upper atmosphere of a planet, and in particular about hydrodynamic escape (Vidal-Madjar et al., 2003). The hot Jupiter HD 209458 b was the first planet to be observed at these wavelengths and found to host a variable atmosphere extending beyond the Roche limit, suggesting that it is escaping (Vidal-Madjar et al., 2003). In addition, heavier atoms and ions have been detected, suggesting that such elements can be dragged up by the evaporation process (Linsky et al., 2010).

Shifting towards longer wavelengths, optical transit spectroscopy can provide information on the presence of alkali metals in the atmosphere of exoplanets. The absorption lines of sodium and potassium, in particular, are shaped by the temperature-pressure profile of the planetary atmosphere. In addition, the amplitude of the lines and the structure of the spectrum out of the lines are representative of the high-altitude hazes and clouds that may exist (Seager and Sasselov, 2000).

Signatures from molecules such as water, methane, carbon monoxide and dioxide, are more prominent at infrared wavelengths, while the absence of such signatures can imply the presence of clouds (Tinetti et al., 2007). Infrared transit spectroscopy is now the most efficient technique used to characterise exoplanet atmospheres.

2.2. Eclipse spectroscopy

The light received from a star-planet system is the sum of three components: a) the stellar light, b) the stellar light reflected by the planet (reflected light), and c) the light emitted by the planet (emitted light). In the infrared, the contribution of the emitted light to the total flux increases with the temperature of the parent star, and, for solar type stars, it dominates over the reflected light.

While the planet is orbiting around the star and spinning around its axis only one of its hemispheres is facing the star (day-side). The other hemisphere will be referred to as the nightside. The reflected light comes only from the day-side and depends on the albedo of the planetary atmosphere. The emitted light comes from both sides and depends on the temperature and the composition of the planetary atmosphere. All the above parameters – albedo, temperature, and composition – can deviate from being uniform across the planetary sphere. Especially for close-in planets, which are usually tidally locked, the difference in temperature and composition between the illuminated and the non-illuminated sides can be significant.

For transiting planets, the orbital configuration is such that the planet also goes behind the star (eclipse). The depth of an eclipse is equal to the total light reflected and emitted by the day side of the planet. Hence, by measuring the eclipse depth we can infer the albedo and the brightness temperature of the day-side of the planet, under the assumption that it is emitting as a blackbody (Charbonneau et al., 2005). The emission component can be described as follows:

$$\delta(\lambda) = \left(\frac{R_P}{R_*}\right)^2 \frac{B(\lambda, T_P)}{B(\lambda, T_*)}.$$

Infrared eclipse observations in spectroscopic mode measure the planetary emission at different depths inside the planetary atmosphere. Such measurements allow us to map the vertical temperature-pressure profile of the atmosphere, along with its chemical composition (e.g. Fortney et al., 2005).

2.3. Phase Curve spectroscopy

Transits and eclipses are happening at very specific times during the planet's orbit. However, during the orbit different parts of the planetary sphere are projected towards the Earth (phases). As explained above, the reflection and emission from the planetary sphere are not uniform. Hence, the varying phases of the planet are causing modulations the light received from the star-planet system – known as phase-variations or phase-curves – which can be converted to 2D longitudinal maps (Cowan and Agol, 2008). The total amplitude of the phase-variations originates from the temperature difference between the

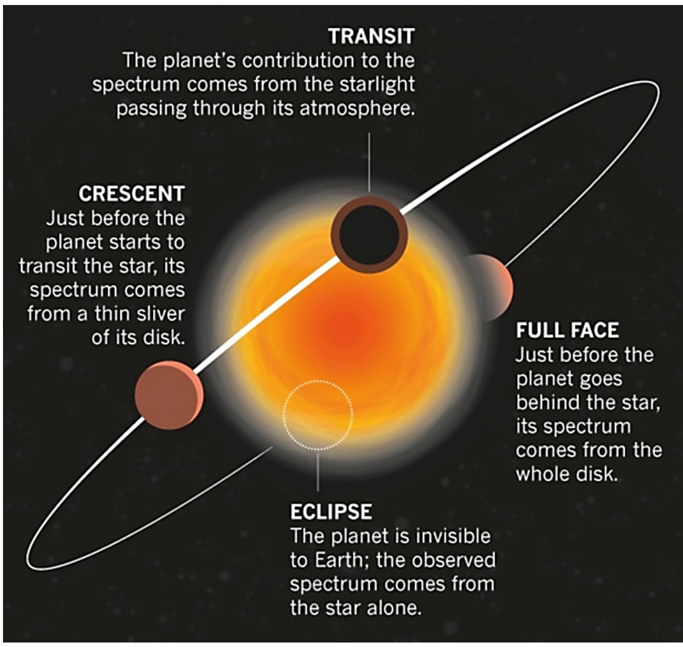

Figure 3: *Summary of observational techniques (Hecht, 2016).*

dayside and the night-side of the planet, while the time difference between the maximum of the phase-curve and the eclipse indicates a longitudinal shift between the hottest area on the observed surface of the planet and the substellar point – the most highly illuminated area of the planet which is expected to be the hottest one. Both observational constrains are providing information on the non-uniform distribution of temperature in the planetary atmosphere, which is a combined result of dynamics, irradiation, heat redistribution, and radiative cooling.

Spectroscopic observations of phase-variations are an invaluable tool for probing the atmospheres of exoplanets as they provide, simultaneous information on the vertical and horizontal thermal structure, as well as on the chemical composition (Stevenson et al., 2014). While such observations are extremely long – even short orbits of exoplanets are of the order of a few days – the wealth of information provided in spectroscopic observations of phase-curves, makes them an important objective for future instruments.

3. The legacy of HST/WFC3

The Wide Field Camera 3 (WFC3) is one of the instruments currently onboard the Hubble Space Telescope (HST), and it was installed in 2009 during the 4th servicing mission of HST. It consists of two independent channels: the ultraviolet/optical channel (UVIS) and the near infrared channel (IR). The latter is equipped with an HgCdTe detector, which is actively cooled down to 145K and has a quantum efficiency close to 90% at wavelengths longer than 0.8 μm, and two grisms suitable for slitless spectroscopy, the G102 (0.8-1.15 μm, R=210 at 1.0 μm) and the G141 (1.075-1.7 μm, R=130 at 1.4 μm).

Since 2012, the WFC3 camera has been used in two different observing modes, the normal (staring) mode, where the telescope pointing is fixed on the target, and the spatial scanning mode, where the telescope is slewing during an exposure, causing the image or the spectrum of the target to move on the detector. The spatial scanning technique allows for a larger number of photons to be collected in a single exposure without the risk of saturation. As a result, overheads are reduced, and the achieved signal-to-noise ratio (S/N) is increased. With the implementation the spatial scanning, WFC3 is today the most successful instrument in performing atmospheric characterisation of exoplanets in the near infrared. Below, some of the most important studies with the WFC3 camera are discussed.

3.1. Gas giants

Since the wavelength range covered by the WFC3 camera is limited (0.8-1.7 μm), molecular signatures from H_2O, CO_2, CH_4, CO, HCN, NH_3, TiO, and VO are the only that can be detected. However, water vapour is more abundant in the atmospheres of exoplanets, and it also absorbs much more strongly than the other molecules at these wavelengths. Consequently, the majority of results so far can be summarised in two main categories: detections and non-detections of water vapour.

The first results using the WFC3 scanning mode were presented by Deming et al. (2013) with the detection of water vapour in the atmospheres of the hot Jupiters HD 209458 b and XO-1 b. Tens of additional such observations

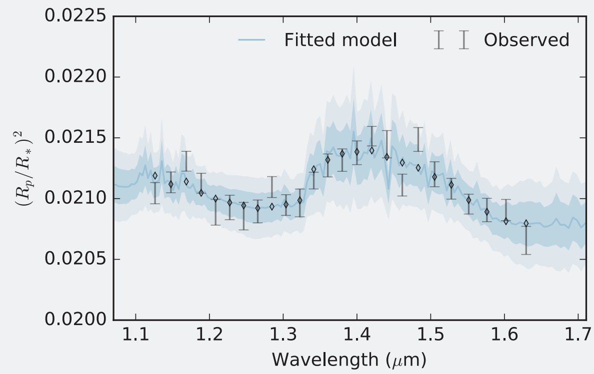

Figure 4: *WASP-39 b: one of the 30 planets analysed in Tsiaras et al. (2018).*

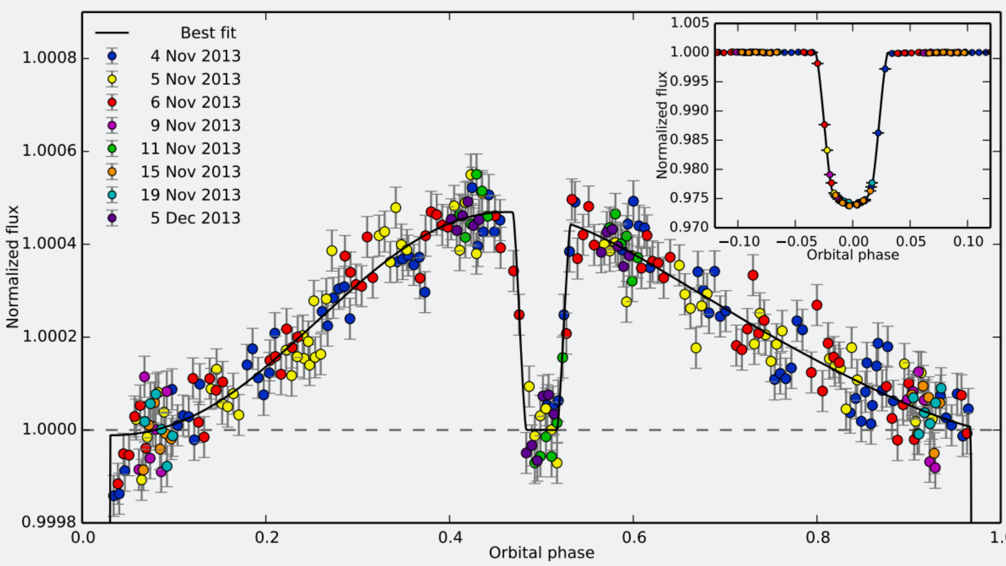

Figure 5: *Phase Curve of WASP-43 b as observed by WFC3 (Stevenson et al., 2014).*

have been made until today reaching more than 50 in total. The largest uniform catalogue produced to date includes 30 hot planets in which 16 have been found to have statistically significant atmospheric detections (Tsiaras et al., 2018).

From the giant planets observed so far, interesting cases are those of WASP-121 b (Mikal-Evans et al., 2019) and KELT-9 b (Changeat and Edwards, 2021) which are tow of the hottest planets observed so far, where metal oxides (TiO, VO) have been detected. Moreover, WFC3 has been used to observe spectroscopically the benchmark planet WASP-43 b (Stevenson et al., 2014).

3.2. Super-Earths

The WFC3 camera is the first instrument to provide atmospheric measurements for planets with masses lower than 10 Earth mass. The first attempts to study the atmospheres of the inflated super-Earths HD 97658 b (Knutson et al., 2014) and GJ 1214 b (Berta et al., 2012; Kreidberg et al., 2014) resulted in flat spectra, suggesting that their atmospheres are either dominated by clouds or are heavier than expected. Furthermore, WFC3 has been used to observe the atmospheres of the planets in the TRAPPIST-1 system. Ttransit observations of six temperate Earth-size planets around the ultra-cool dwarf TRAPPIST-1 – planets b, c, d, e, f (de Wit et al., 2018), and g (Wakeford et al., 2019) – have not shown any molecular signatures and have excluded the presence of cloud-free, H/He atmospheres around them.

3.2.1. 55 Cancri e

At a distance of only 12 pc, 55 Cancri is a Sun-like star (G8V type) hosting an extremely interesting planetary system with five planets, all discovered via radial velocity measurements. The fourth planet to be discovered, 55 Cancri e (McArthur et al., 2004), was the least massive planet discovered until then, with a minimum mass of 14.21 Earth masses, orbiting the parent star at 0.04 AU every 2.808 days. However, Dawson and Fabrycky (2010) revised these values, reporting a period of 0.7365 days and a minimum mass of 8.3 Earth masses, giving 55 Cancri e a high chance (25%) of causing transit events. 55 Cancri e is an "exotic" example of a super-Earth as it orbits very close to the host star and consequently the temperature on its surface is high – i.e. hotter than 2000 K. Transits caused by 55 Cancri e were observed from space, with the Spitzer Space Telescope (Demory et al., 2011; Gillon et al., 2012) and the MOST Space Telescope (Winn et al., 2011; Dragomir et al., 2014), confirming its small size.

Analysis of WFC3 spectra by Tsiaras et al. (2016) (Figure 6) came to the conclusion that the atmosphere of 55 Cancri e is light-weighted with a significant H/He component. Furthermore, no evidence of water vapour has been found while a potentially high C/O ration was reported. This detection was the first of an atmosphere around a super-Earth and its presence is also supported by the dynamics necessary to explain the temperature difference between its day and night side (Kite et al., 2016). However, other studies were not able to detect the atmosphere using different methods (Deibert et al., 2021), leaving the case of 55 Cancri e as an open question for future instruments.

3.2.2. K2-18 b

K2-18 b was discovered in 2015 by the Kepler spacecraft, and it is orbiting around an M2.5 dwarf star, 34 pc away from the Earth. Based on the planet's characteristics, it orbits within the star's habitable zone, with an effective temperature between 200 K and 320 K. HST/WFC3 observed eight transits of K2-18 b and multiple studies that analysed those data (Tsiaras et al., 2019; Benneke et al., 2019; Madhusudhan et al., 2020) came to the same conclusion: the atmosphere of K2-18 b hosts water vapour (Figure 7). This result makes K2-18 b the first super-Earth with a detect-

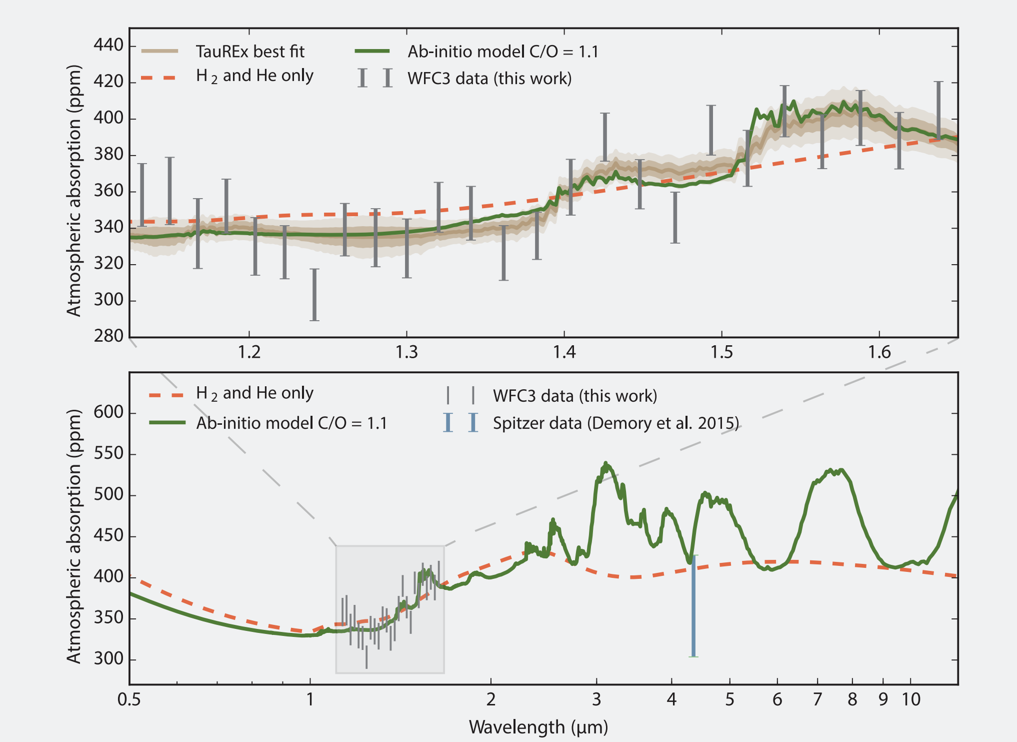

Figure 6: *WFC3 spectrum of 55 Cancri e and best-fit, compared to ab-initio estimates (Tsiaras et al., 2016).*

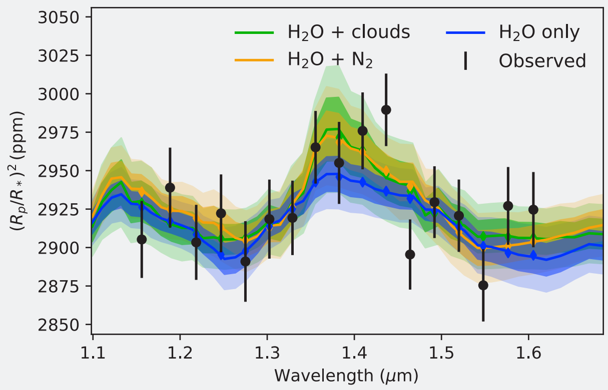

Figure 7: *WFC3 and best-fit models for the three different scenarios (Tsiaras et al., 2019).*

able atmosphere and with a molecular detection. However, while the water vapour feature has been confirmed, it is not possible to constrain the exact water abundance (relative to H/He) due to the narrow wavelength coverage of the WFC3 camera. In Tsiaras et al. (2019) thee possible scenarios are identified:

- A secondary atmosphere with a mean molecular weight explained by water vapour (up to 50%) additionally to H/He.
- A secondary atmosphere with traces of water vapour additionally to one or multiple undetectable absorbers (e.g. N2) and H/He.
- A cloudy primary atmosphere composed mainly by H/He and traces of water vapour.

Most importantly, the thickness of the atmosphere cannot be inferred from the WFC3 observations. This information is critical to constrain the bulk nature of the planet – i.e., whether K2-18 b is an Ocean planet with a liquid surface or there is a thick H/He atmosphere. However, the updated mass and radius of the planet Benneke et al. (2019) place the planet in the category of the larger low-mass planets, known as "mini-Neptunes", reducing substantially the possibilities of a surface being present.

3.2.3 LHS 1140 b

With a radius of 1.7 Earth radii and a density of 7.5 gcm^{-3}, LLHS 1140 b is likely to be a rocky world (Ment et al., 2019) and, with an equilibrium temperature of –235 K, it is within the conservative habitable-zone of its star. While recent ground-based observations were not precise enough to constrain atmospheric scenarios (Diamond-Lowe et al., 2020), reconnaissance with Hubble WFC3 (Edwards et al., 2021) shows modulation in the transit depth over the 1.1-1.7 μm wavelength range. This modulation can be explained by the presence of water vapour, but the S/N provided by HST is not enough to come to a strong conclusion (2.6σ). However, this this the first rocky habitable-zone planet for which there is a hint towards the presence of water vapour and will be a prime target for future instruments.

3.2.4 GJ 1132 b

Based on WFC3 observation, Swain et al. (2021) reported the detection of a secondary atmosphere around an Earth-sized planet, GJ 1132 b, which has a mass of 1.66 Earth masses and a radius of 1.16 Earth radii, making it a terrestrial planet (Bonfils et al., 2018). The transmission spectrum suggested the presence of aerosols, HCN and CH_4 in a low mean molecular weight atmosphere, inferring the presence of hydrogen. Since GJ 1132 b has most likely lost his primordial H/He envelope through photoevaporation the study suggests that the atmospheric signal can be explained by mantle out-gassing. On the contrary, Mugnai et al. (2021) analysed the same dataset, finding no evidence for the presence of an atmosphere.

4. James Webb Space Telescope and Ariel

Despite the large number of first discoveries, HST is limited as far as the wavelength coverage is concerned. In the near future, new space facilities will be able to deliver data of much better quality. These facilities are the James Webb Space Telescope (JWST) and ESA's M4 mission, Ariel (Tinetti et al., 2018, 2021). In addition, the TESS mission, which is currently in operation, is already delivering and will continue to deliver planets that will be within the reach of these telescopes, as TESS (in contrast to Kepler) is mainly observing nearby, bright, stars.

JWST is planned to be launched in October 2021 and one of its key science goals will be to explore the atmospheres of exoplanets. With a six-meter-long mirror, a wavelength coverage (not simultaneous) between 0.6 and 12 μm (for exoplanet-related observations) and the ability to deliver continuous, long-duration observations, JWST will bring a new window into the atmospheric composition and dynamics for exoplanets. During the lifetime of the mission, JWST will be able to observe up to 150 exoplanets (Cowan et al., 2015). JWST will be the first instrument to provide detailed transmission, emission and phase spectra of both gas giants and super-Earths, due to the increase S/N. With such data it will be possible to put better constraint on the planetary C/O ratios and metallicities, to construct 3D chemical and dynamical maps of the atmospheres, study the nature of clouds and hazes and probe the molecular composition of habitable-zone planets.

Further in the future, Ariel is planned to be launched in 2028/9 and will be the first space telescope dedicated to the characterisation of exoplanetary atmospheres. With a one-meter-long mirror and simultaneous wavelength coverage between 0.5 and 7.8 μm, Ariel will observe 1000 exoplanets. The observations of Ariel will be organised as a survey, in 4 Tiers: all the planets will be studied at low resolution to examine the detectability of their atmosphere (to check if there is an extended envelop or if there are clouds covering the molecular signal), from them about half will be further monitored to extract their molecular composition while for a smaller sample (~50) further observations will aim at higher precision chemistry and variability. Finally, there will also be a special group of planets to be monitored throughout their full orbit (phase curves). With the large numbers provided by Ariel, it will give us the opportunity to study the planets as celestial bodies from a population perspective for the first time in history.

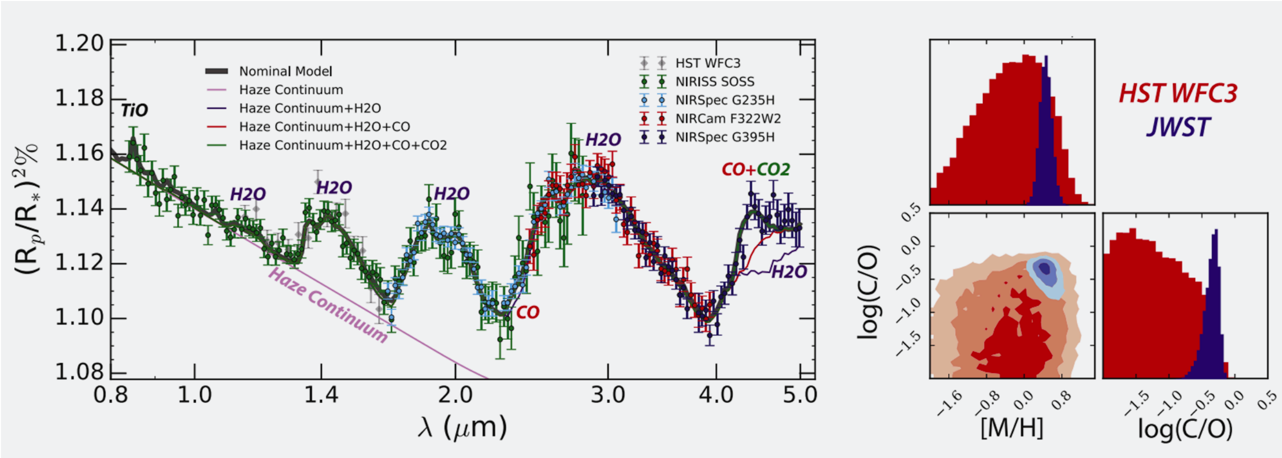

Figure 8: *Performance Comparison between HST and JWST (Bean et al., 2018).*

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