# HIPPARCHOS

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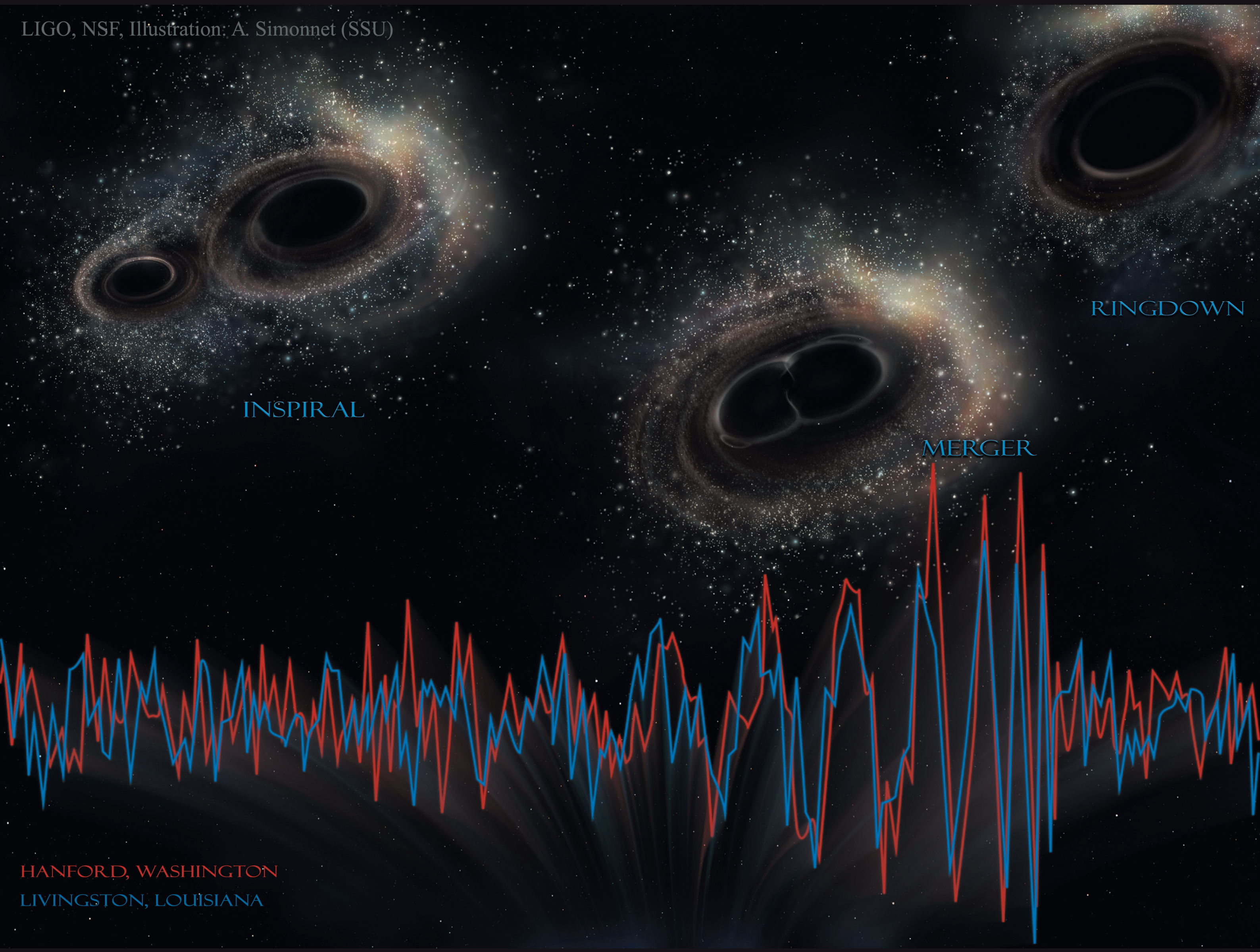

HIPPARCHOS

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



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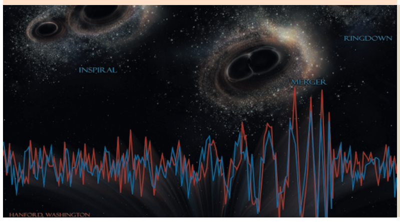


**Cover Image:** A schematic merger of two supermassive black holes used to interpret the celebrated first detection of gravitational waves by the LIGO consortium, announced on February 11, 2016.

Credit: The National Science Foundation, the LIGO Consortium and A. Simonnet of the Sonoma State University, USA.

# Message from the President

May 16, 2016

***Dear Colleagues,***

Over the last two years I have had the pleasure and the privilege of working closely with a remarkable team of young Colleagues in the Council of our Society. Hel.A.S. over the years has established a number of activities which we have worked hard to maintain and enrich. We tried to improve the Society's webpage and established an account on Twitter (@elaset_tweet) to initiate a fast link of communication with Society members. We also tried to maintain the high standards Hipparchos has reached, while the Society's electronic newsletter was published regularly every month with a variety of news and events. We further initiated a new travel grant for our Junior Members. The 12$^{th}$ Hellenic Astronomical Conference was hosted last year by the Aristotle University of Thessaloniki and was very well attended, especially by Junior Members. The invited talks and the quality of the scientific work presented were outstanding. Academician Stamatios Krimigis delivered a fascinating keynote talk on "The first human journey to the galaxy" in a packed auditorium in the New City Hall of Thessaloniki. For this leap year between meetings, the 2$^{nd}$ Hel.A.S. Summer School is planned in Athens in June.

Year 2016 has proved to be a history maker in astronomy and astrophysics. The detection of gravitational waves by the LIGO consortium was a remarkable achievement awaited for a century that has now opened up a new observational window for the study of extreme astrophysical processes in the Universe. Nikolaos Stergioulas of the University of Thessaloniki reviews in this issue the recent work on the generation of gravitational waves by the merging of binary neutron stars. The hopes and stakes are high, namely that the new generation of detectors will reveal the properties of a neutron star's equation of state. The detection of gravitational waves was a triumph achieved by the synergy between Astrophysics, Computational Astrophysics and innovative technology.

Vasiliki Pavlidou of the University of Crete discusses a very ambitious project related to the exploration of optical emission from blazars and the significance of monitoring the polarization, since this information reveals the magnetic field structure of blazar jets. The RopoPol program for the polarimetric monitoring of blazar emission was established in 2013 as a collaboration between the University of Crete and Caltech, The Max-Planck Institute for Radio Astronomy, the Inter-University Center for Astronomy and Astrophysics in India and the Nicolas Copernicus University in Poland. The RopoPol collaboration also explores innovative observational techniques with strong astrophysical and numerical skills.

The formation and propagation of Coronal Mass Ejections (CMEs) and their impact on Earth's magnetosphere is discussed by Spiros Patsourakos of the University of Ioannina. Based on a synergy between numerical simulations and satellite data, mostly provided by the STEREO and SDO space missions, several new capabilities opened up for CME studies, in particular, and Space Weather research, in general, based on the use of a new generation of solar and heliospheric instruments. The review reflects an unprecedented collaboration involving the majority of the Greek space physics community and prominent fellow researchers abroad.

Let me emphasize at this point that all three articles show a common underlying trait, namely the prolific interaction between innovative work in astrophysics, simulations and cutting-edge instrumentation. I strongly recommend that our members read them.

This year also features a large array of diverse astronomy and astrophysics meetings in Greece. Prominently among them, our Society is hosting the European Week of Astronomy and Space Science (EWASS), which will be held in Athens, from the 4$^{th}$ to the 8$^{th}$ of July 2016. We provide a brief presentation of most of the meetings in this issue. This year also marked the conclusion of several ambitious research projects initiated in 2012, funded by the operational program "Education and Life Long Learning" of the European Social Fund. A new generation of projects are currently underway, funded by the European Commission Horizon 2020 Programme. Our Society has worked hard toward the formation of a National Strategic Program on Astronomy and Space Research based on thoroughly evaluated national needs and respective opportunities provided by the European Space Agency and the European Commission. In spite of these efforts, a National Space and Astrophysics Committee that would formulate and implement such a roadmap has not yet been formed. Let us hope that its establishment remains high in the agenda of the involved supervising entities.

There are other areas where our Society could do more in the near future. Public outreach and educational activities have not yet evolved to the level we had hoped for, mainly because of a highly intermittent –or even totally absent– funding. Keeping at the forefront of our respective research areas ensures that

# Message from the President (cont.)

the members of our Society remain credible speakers, as evidenced by the numerous invitations for public talks in wide audiences. We should also have increased our involvement with school activities and school-specific projects, including planetarium visits and shows. Active promotion of astronomy and astrophysics in the entire array of elementary and intermediate education is the best one can do to avert a future shortage of Greek astronomy and astrophysics professionals.

On a personal note, after forty years of active research and teaching in astrophysics-related subjects I am stepping down from teaching and return to full-time research with the enthusiasm of a "young" post doc. I am so pleased to see my generation of astronomers and astrophysicists, after returning back to Greece from several years abroad, looking upon the young generation of professionals with a smile of satisfaction and a recommendation "keep walking, we still have a long way to go".

*Loukas Vlahos*
*President of Hel.A.S.*

## Celebrating Juno's Arrival at Jupiter: Tuesday, 5 July 2016, Athens

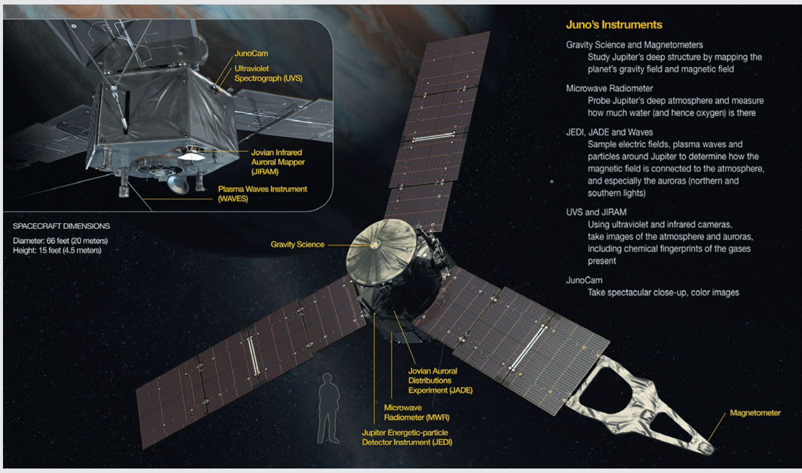
Jupiter is by far the largest planet in the solar system. Humans have been studying it for hundreds of years, yet still major questions about this gas world remain unanswered. Clues about the origins of our solar system may be hidden beneath the clouds and massive storms of Jupiter's upper atmosphere. The Juno spacecraft will, for the first time, see below Jupiter's dense cover of clouds (this is why the mission was named after the Roman goddess, who was Jupiter's wife, and who could also see through clouds).

Juno's primary goal is to reveal the story of the formation and evolution of Jupiter. Using long-proven technologies on a spinning spacecraft placed in an elliptical polar orbit, Juno will observe Jupiter's gravity and magnetic fields, atmospheric dynamics and composition, and the coupling between the interior, atmosphere and magnetosphere that determines the planet's properties and drives its evolution. An understanding of the origin and evolution of Jupiter, as the archetype of giant planets, can provide the knowledge needed to help us understand the origin of our solar system and planetary systems around other stars.

Juno was launched from Cape Canaveral Air Force Station in August 2011. After a five-year journey the spacecraft is scheduled to reach Jupiter on 4 July 2016. Juno will then fire its main engine and slip into orbit around the giant planet to begin its scientific mission. The spacecraft will orbit Jupiter 33 times, skimming to within 5,000 kilometers above the planet's cloud tops every 11 days, for approximately one year*.

To celebrate Juno's orbit insertion, a **public event** will be organized in the context of the first **Europlanet Outreach Innovation Day**

**When:** Tuesday, 5 July 2016, 7:00-8:30 pm
**Where:** Coral Hotel Athens, Faliro




A round table discussion will be held with the participation of:

**Dr. Scott Bolton, Juno Principal Investigator** (Southwest Research Institute, San Antonio) on live link from the Jet Propulsion Laboratory

**Prof. Michel Blanc**, Juno Co-Investigator (L'Observatoire Midi-Pyrénées) on live link from the Jet Propulsion Laboratory

**Dr. Athena Coustenis**, Director of Research CNRS (Paris Observatory), Europlanet Deputy Coordinator

**Dr. Iannis Dandouras**, Director of Research CNRS (IRAP Toulouse)

**Prof. Ioannis Daglis**, Professor of Space Physics (National & Kapodistrian University of Athens)

* Information provided from Juno press kit and mission fact sheet. More information on Juno: https://www.nasa.gov/mission_pages/juno/

# Athens Effective Solar Flare Forecasting (A-EFFort): the first flare prediction service of ESA's Space Situational Awareness (SSA) Programme

ESA/SSA's latest Expert Service Centre, the RCAAM of the Academy of Athens, has delivered to the Agency its first fully automated, pre-operational solar flare forecasting service. Users can register freely and opt for e-mail alerts in case of significant flare probabilities.

A-EFFort service web site:
http://a-effort.academyofathens.gr

ESA/SSA Space Weather Portal for registration:
http://swe.ssa.esa.int/web/guest/request-for-registration

by M. K. Georgoulis, K. Tziotziou, K. Themelis, M. Magiati, G. Angelopoulou & M. Zoulias
Research Center for Astronomy and Applied Mathematics (RCAAM), Academy of Athens, Greece

Flares are historically the first known manifestation of solar magnetic eruptions. They occur close to the photospheric surface of the Sun and are due to the extreme solar magnetic fields, the strongest in the solar system. Tangled, complex magnetic lines of force find their way into relaxation by snapping and reconnecting to more stable arrangements, releasing magnetic energy up to $10^{26}$ J within minutes. This energy is equivalent to an unimaginable one trillion times the energy of the Hiroshima atomic bomb, with typical flares releasing energies of the order several billion times that amount.

Flare magnetic energy floods the entire electromagnetic spectrum in terms of flare-induced emission, intensely heats a significantly larger volume than the flare-initiation volume, and affords the kinetic energy of near-relativistic accelerated electrons and heavier ions in the solar atmosphere. "Hard" flare emission (non-thermal X-rays and γ-rays) can harm both humans and sensitive electronic equipment in orbit while flare-energized particles, should they hit the terrestrial ionosphere, can cause disruptive interference and even radio blackouts on communications. Obviously, no early warning exists for flare photons, whereas only a slim window of the order tens of minutes exists for flare-accelerated plasma particles, in case of suitable inner-heliospheric magnetic connectivity. Clearly, then, major flares must be predicted ***before*** they are triggered in the Sun.

In a yearlong effort that concluded in December 2015, the A-EFFort team managed to transition a purely scientific tool into a pre-operational federated service of ESA's Space Weather (SWE) Portal, owned by the Agency's Space Situational Awareness (SSA) Programme. The A-EFFort service is physically located at RCAAM premises (Figure 1).

The A-EFFort system translates magnetic complexity in solar flare "hotspots", known as active regions, into major flare probabilities within the next 24 hours, effective immediately (i.e., with zero latency) and updated every 3 hours. A blend of fundamental solar physics, pattern recognition, and Bayesian statistics has been employed for this purpose. Initially, active regions are identified and extracted from full-Sun magnetograms via an Automatic Active Region Identification Algorithm[1,2]. Then, a parameter coined the Effective Connected Magnetic Field Strength ($B_{eff}$) quantifies the envisioned coronal magnetic connectivity of each active region at a given time[3,4]. Finally, the Laplace's rule of succession in Bayesian statistics[5] applied to a historical magnetogram archive links each $B_{eff}$-value to a categorical forecast probability for preset flare classes and forecast windows (i.e., 24 hours, for GOES M1-, M5-, X1- and X5-class flares).

The service infrastructure consists of a failsafe configuration of two identical, "heartbeat"-connected, servers forming a high-availability cluster with one running the software code and another in standby mode, ready to take over should the operating server become disabled. The software architecture and data storage facility relies on a virtual machine rooted jointly on both servers. This ensures the uninterrupted, 24/7 operation of the service for nominal power and internet provision. Near-realtime solar magnetic field measurements necessary for the calculations flow directly from the Joint Science Operation Center of NASA's Solar Dynamics Observatory (SDO) Helioseismic and Magnetic Imager (HMI)[6] in Stanford University, USA. The SDO/HMI expert team kindly assisted the A-EFFort team in the au-


***Figure 1:*** The A-EFFort facility at RCAAM premises. The service operates in a dedicated, temperature-controlled server room.

tomated downloading and preprocessing of the data used for the calculations.

A-EFFort is a fully automated service, ESA's first and the fourth in the world that requires no human intervention. It is also comprehensively and successfully validated on the historical database used for acquiring its statistics. Its online interface features a familiar street-light forecast assessment (green, orange, red, for increasing major flare risk – see Figure 2) and is openly accessible following a free registration process at ESA's SSA/SWE Service Portal. The service itself has been also validated for its first three months of operation, showing encouraging results in spite of evidently poor statistics. A peer-reviewed paper describing the service and its validation in sufficient detail is currently in preparation.

The A-EFFort service agreement with ESA/SSA calls for a continuous operation of the service at least until September 2018, with further ESA decisions expected by then.

In spite of the underwhelming solar activity in solar cycle 24 the A-EFFort service has already claimed its first successes: Figure 3 shows one of these, with the service issuing an alert for a GOES M3.9-class flare that finally occurred on November 9, 2015. In case of significant flare probabilities, e-mail alerts are forwarded to registered users. For the particular flare, an alert was in effect for flares of GOES class M1.0 and higher. We are looking forward to more successes, at the same time scrutinizing the innovative service to the best of our ability.

## Acknowledgements:

We are grateful to Drs. Monica Bobra and Charles Baldner of the SDO/HMI team at Stanford University for their crucial support in downloading and preprocessing full-Sun near-realtime magnetograms. The A-EFFort service is supported and maintained by ESA Contract number 4000111994/14/D/MRP.

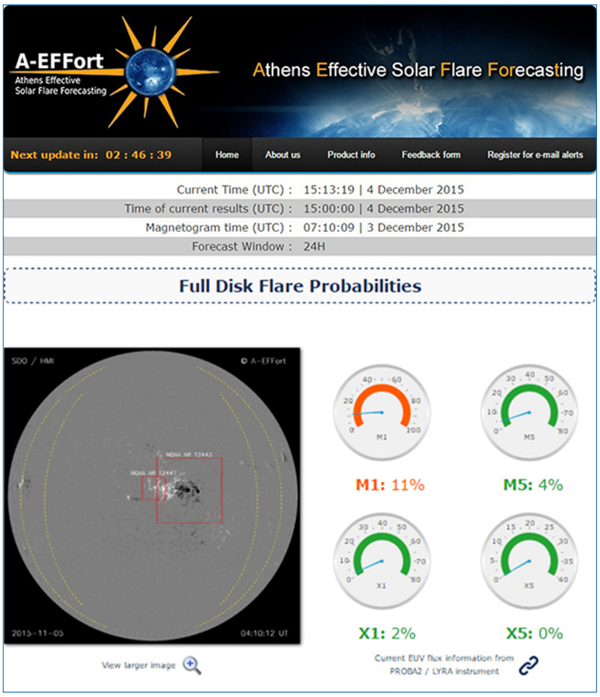



*Figure 2:* Example home page of the service, with the processed, latest full-disk SDO/HMI magnetogram on the left and the full-disk major-flare probabilities on the right. On the top part, all times are UTC, while a timer on the left provides the remaining time until the next forecast.

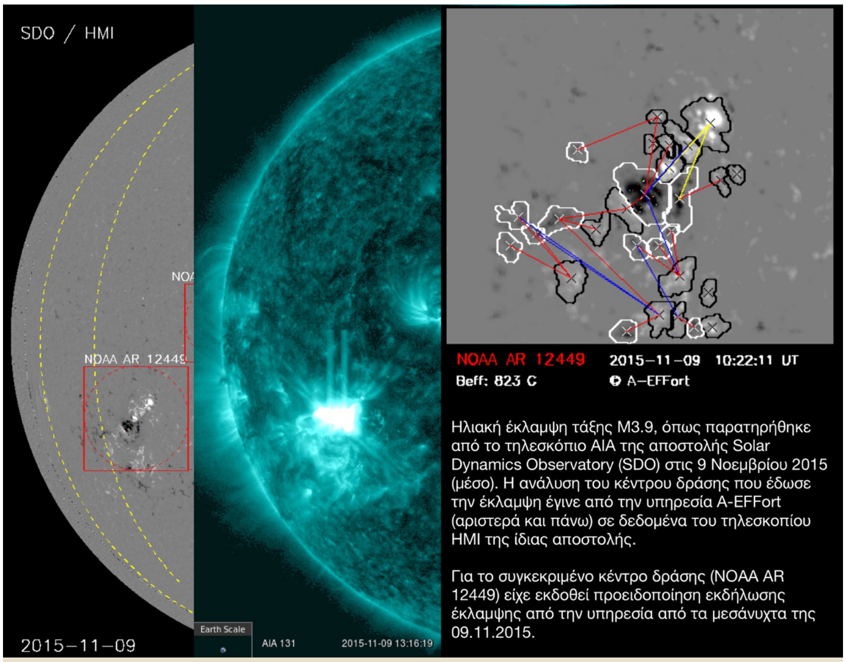



*Figure 3:* A successful A-EFFort service prediction of a major (GOES class M3.9) solar flare. Shown are (left) part of the processed SDO/HMI magnetogram showing the host NOAA active region (AR) 12449, (middle) an SDO/AIA image of the flare in the extreme ultraviolet (131 Å), and (right) the particular processing of the host active region. A 24-hour alert for flares of GOES class M1.0 and higher had been issued at 00:00 UTC on 9 November 2015, with the flare occurring at 12:49 UTC of that day.

## References

1. LaBonte, B. J., Georgoulis, M. K., & Rust, D. M., 2007, *Astrophys. J.*, **671**, 955
2. Georgoulis, M. K., Raouafi, N.-E., & Henney, C. J., 2008, *ASP Conf. Series*, **383**, 107
3. Georgoulis, M. K. & Rust, D. M., 2007, *Astrophys. J.*, **661**, L109
4. Georgoulis, M. K., 2012, *Astroph. Space Sci. Proc.*, **30**, 93
5. Jaynes, E. T. & Bretthorst, G. L., 2003, *Probability Theory*, Cambridge U. Press, pp. 154-156
6. Scherrer, P. et al., 2012, *Solar Phys.*, **275**, 207

# GRAVITATIONAL WAVES: A new observational tool for understanding the nature of neutron stars

by Nikolaos Stergioulas

*Department of Physics, Aristotle University of Thessaloniki, Greece*

**Abstract:**

*With the first direct detection of gravitational waves from the coalescence of a binary black hole system accomplished, the next main target of gravitational wave astronomy is the merger of binary neutron star systems. Through the detection of the main oscillation frequency in the post-merger phase, the radius of typical neutron stars could be determined to high accuracy. With several such observations, the radius of neutron stars with maximum mass could also be constrained, leading to a determination of the high-density equation of state. With plans for new upgrades and for much more sensitive new detectors under way, the goal of revealing the neutron star equation of state seems within reach.*

## Introduction

The celebrated first direct detection of gravitational waves from the coalescence of a binary black hole system (Abbott et al. 2016) has opened a new observational window for studying astrophysical processes in the universe. The first gravitational wave source, GW140915, allowed for an unprecedented test of General Relativity in the strong-gravity regime. A larger number of future observations will provide new constraints on extended theories of gravity, while new insights on stellar evolution as well as cosmological implications are expected.

The next main target of gravitational wave astronomy is the detection of binary neutron star (BNS) mergers, with the main aim of constraining the hitherto uncertain equation of state (EOS) of matter at high densities. The continuous improvement in sensitivity of the Advanced LIGO (Aasi et al. 2015) and Advanced VIRGO (Acernese et al. 2015) detectors as well as the construction of the KAGRA detector (Aso et al. 2013) is expected to lead to the first direct detection of gravitational waves from the inspiral phase of BNS mergers. This will give us the chance to extract information on the structure of neutron stars from the gravitational wave signal. Specifically, one of the outcomes that is eagerly anticipated is to constrain the neutron star radius with much better accuracy than current observations (see Özel and Freire, 2016, for a review of the current status based on observations using the electromagnetic spectrum). By inverting the mass-radius relation of neutron stars, the EOS can be determined, which will lead to significant progress in theoretical physics.

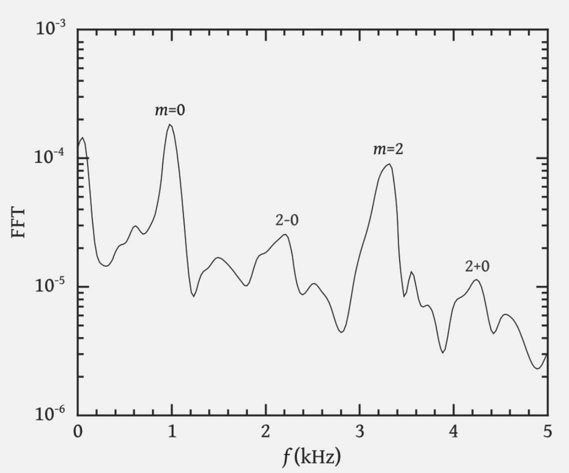
Constraints on the neutron star radius could be obtained either from the inspiral phase, where radius information is encoded in the phase evolution of the gravitational wave signal via the impact of tidal interactions (see Flanagan & Hinderer, 2008; Read et al. 2009; Bernuzzi et al. 2012; Damour, Nagar & Villain, 2012 and Duez 2010 for a review), or from the post-merger phase, where radius information is encoded in the frequency of oscillations excited in the newly-formed remnant (see Shibata 2005; Bauswein & Janka, 2012; Bauswein et al. 2012; Bauswein, Stergioulas & Janka, 2014; Bauswein & Stergioulas, 2015 and references therein). In the former case, a few tens of inspiral detections at 100 Mpc will be required to arrive at radius constraints for typical neutron stars on the order of 10%. In the latter case, even a single post-merger detection will suffice to constrain the radius of typical neutron stars to within 4%, while a few detections may allow a good estimate of the radius of neutron stars with maximum mass, thus revealing the EOS up to the highest allowed densities.

## Binary neutron star mergers

Remnants of neutron-star mergers are massive, hot and differentially rotating. Depending on the mass configuration of the system and on the EOS, a BNS merger may result in prompt collapse to a black hole (typical for a combination of high-mass and soft EOS) or in the formation of a stable or quasi-stable neutron star remnant which again, may or may not collapse to a black hole, depending on its mass and the EOS, while transient nonaxisymmetric deformations and quadrupolar oscillations in such a remnant typically give rise to a structured, high frequency (1-4 kHz) GW spectrum and a signal lasting about 10-100ms. The dominant post-merger oscillation frequency $f_{peak}$ is due to the excitation of the m=2 linear fundamental quadrupolar oscillation mode in the remnant (see Stergioulas et al. 2011 and Bauswein et al. 2015 for an unambiguous identification). A detailed analysis of the post-merger GW frequency spectrum and its comparison to the spectrum of oscillations in the matter inside the neutron star revealed the presence of several quasi-linear combination frequencies, with the dominant one being the difference $f_{2\text{-}0}$ between the m=2 frequency $f_{peak}$ and the m=0 quasi-radial frequency $f_0$ (Stergioulas et al. 2011), see Fig. 1.

Recently, a deeper understanding of the features of post-merger GW spectra emerged in Bauswein & Stergioulas (2015), where it was shown that an additional, fully nonlinear feature, $f_{spiral}$, exists in the spectrum. This is produced by the orbital motion of antipodal bulges, which form during the merging as a spiral deformation and then orbit around the inner remnant for a few milliseconds, see Fig. 2. The relative strength between the $f_{2\text{-}0}$ and $f_{spiral}$ frequencies depends on the binary mass and the EOS.

**Figure 1:** Frequency spectrum of fluid oscillations in the interior of a post-merger remnant, for a merger of a $1.35M_{\odot}$ + $1.35M_{\odot}$ binary system with the LS 180 EOS. Apart from the linear $m$=0 quasiradial and $m$=2 quadrupolar frequencies, their quasilinear combination frequencies $f_{2\text{-}0}$ and $f_{2+0}$ are also present, forming a equispaced triplet around the $m$=2 frequency. Figure from Stergioulas et al. (2011).



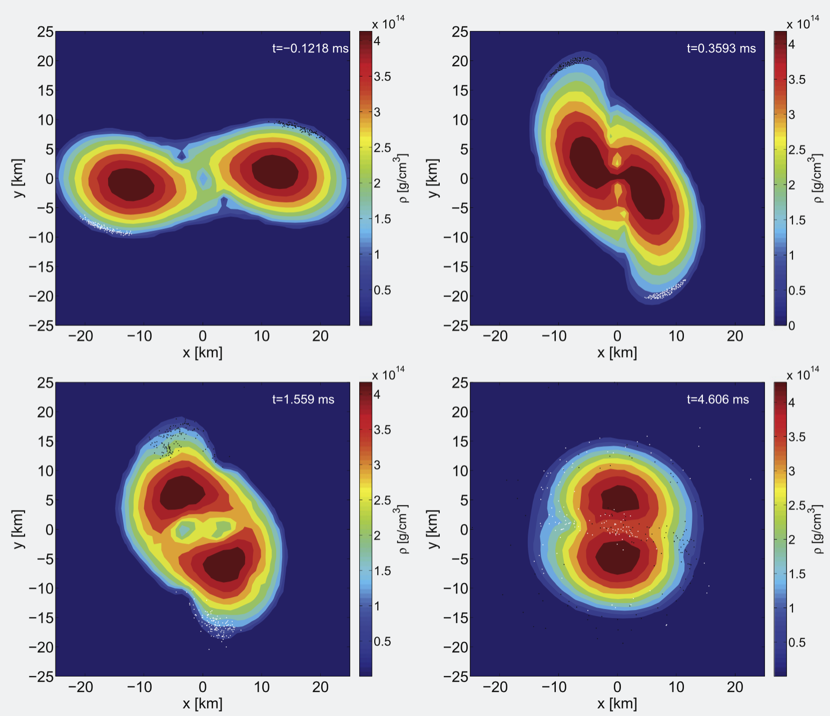
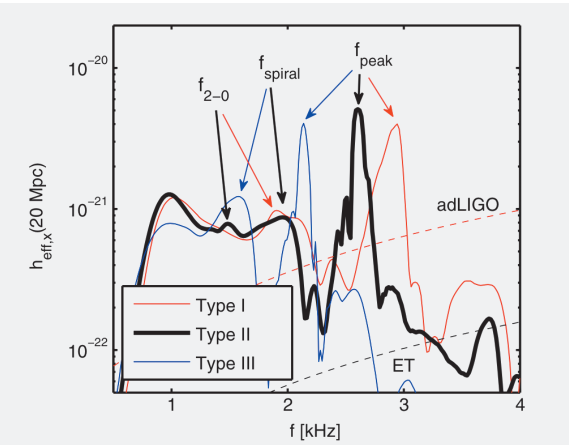




**Figure 2:** Evolution of the rest-mass density in the equatorial plane for a $1.35M_{\odot}$ + $1.35M_{\odot}$ merger with the TM1 EOS (selected iso-density contours are shown). Black and white dots indicate the positions of selected fluid elements constituting the antipodal bulges, which generate a distinct peak ($f_{spiral}$) in the GW spectrum. Figure reproduced from Clark et al. (2016).

**Figure 3:** Gravitational wave spectra for a merger of a $1.35M_{\odot}$ + $1.35M_{\odot}$ binary system, obtained for three different candidate equations of state (DD2 - black, NL3 - blue, LS220 - red). Dashed lines show the anticipated unity signal-to-noise-ratio sensitivity curves of Advanced LIGO and of the proposed Einstein Telescope. Figure reproduced from Bauswein & Stergioulas (2015).




One can identify three different types of spectra: high-mass/soft EOS binaries produce spectra where the dominant secondary peak is $f_{2\text{-}0}$ (Type I mergers). For intermediate binary masses and EOS stiffness, both the $f_{spiral}$ and $f_{2\text{-}0}$ features are present with roughly comparable amplitude (Type II mergers). Low-mass/stiff EOS binaries produce spectra with a strong $f_{spiral}$ peak and an absent $f_{2\text{-}0}$ feature (Type III mergers), see Fig. 3.

## Frequency-radius relation

Characterizing the frequency content of GW signals from the post-merger phase provides unique opportunities for GW asteroseismology: the dominant post-merger oscillation frequency $f_{peak}$ was found to exhibit a tight correlation with the radius of non-rotating neutron stars (Bauswein & Janka, 2012; Bauswein et al. 2012). For equal mass mergers with a total binary mass of 2.7 $M_{\odot}$, this relation is

$$R_{1.6}[\text{km}] = 1.1\,(f_{peak})^2 - 8.6\,f_{peak} + 28 \quad (1)$$

where $R_{1.6}$ is the radius of a nonrotating neutron star of 1.6 $M_{\odot}$ and $f_{peak}$ is given in kHz. Similar relations hold for other binary masses. Rescaling $f_{peak}$ by the total binary mass $M_{tot}$, leads to the universal relation shown in Fig. 4. The systematic uncertainty in the empirical fit is about 200-300m. The radius-frequency relation (1) exists because binary neutron star mergers form in a restricted parameter space, which is determined only by their initial masses and the EOS. Hence, their quadrupole oscillation frequency is related to the average density, as in the case of the empirical relations constructed for nonrotating neutron stars (Andersson & Kokkotas, 1998), which form the basis of gravitational-wave asteroseismology (see also Doneva & Kokkotas, 2015, and references therein for the case of single, rotating neutron stars).

Since the majority of pre-merger neutron stars are likely to have masses in the range of about 1.35 ± 0.15 $M_{\odot}$, the pre-merger waveforms are limited to probing the structure of neutron stars in that mass-range, while the post-merger signal allows us to probe the densities that occur in heavier neutron stars of 1.6 $M_{\odot}$. This is because the central density of the remnant of a 1.35 + 1.35 $M_{\odot}$ merger is close to the central density of a 1.6 $M_{\odot}$ nonrotating star.

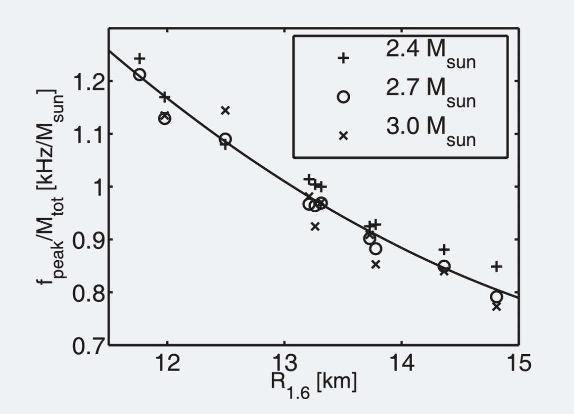
## Revealing the equation of state

While a single detection of $f_{peak}$ in the post-merger GW signal of a typical merger event will suffice to determine the radius of 1.6 $M_{\odot}$ neutron stars with high accuracy, this will still leave open the possibility of several candidate EOSs differing in radius at higher masses. Bauswein et al. (2014) presented a novel method for revealing the EOS of high-density neutron star matter, which relies on a small number of detections of the peak frequency in the post-merger phase of BNS mergers with relatively low masses (in the most likely range of expected detections). From a few such low-mass observations, one can construct the derivative of the peak frequency versus the binary mass. One can then extrapolate the above information to the highest possible mass (the threshold mass for black hole formation in a binary neutron star merger). In turn, this allows for an empirical determination of the maximum mass of cold, nonrotating neutron stars to within 0.1 $M_{\odot}$, while the corresponding radius is determined to within a few percent. Combining this with the determination of the radius of cold, nonrotating neutron stars of 1.6 $M_{\odot}$, allows for a clear distinction of a particular candidate equation of state among a large set of other candidates. The proposed method is particularly appealing, because it reveals simultaneously both the moderate and the very high-density parts of the EOS, enabling two different mass-radius relations to be distinguished even if they are similar at typical neutron star masses, see Fig. 5.

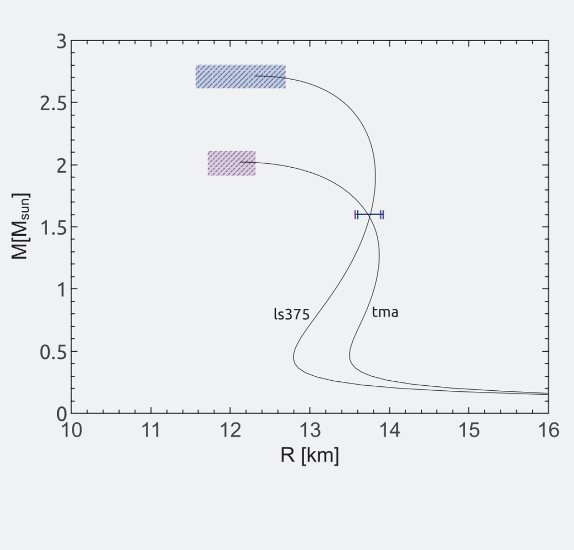
## Prospects for detection

Realistic detection prospects of the main peak in the post-merger GW spectrum were first estimated using a simple burst algorithm in Clark et al. (2014). A more effective frequency-domain template for post-merger oscillations was presented in Clark et al. (2016). This template is based on a *principal component analysis* (PCA) of waveforms obtained through numerical simulations of BNS mergers for a variety of neutron star EOSs and binary mass configurations. This was enabled by the unified picture of the post-merger evolution that was presented in Bauswein & Stergioulas (2015), allowing for the construction of a rescaled, mean spectrum, while deviations from the mean are decomposed using a small number of basis functions. The template achieves >90% match across a wide variety of merger waveforms and strain sensitivity spectra for current and proposed GW detectors. The typical statistical uncertainty in the determination of the dominant post-merger oscillation frequency $f_{peak}$ within a noisy gravitational wave signal is about 140Hz. Using the recently derived empirical fit between $f_{peak}$ and the neutron star radii (and taking into account its systematic error of 200-300m) the radius of a typical neutron star can be constraint with a maximum uncertainty of about 3-4% (depending on the true EOS).

Table 1 (adapted from Clark et al. 2016) summarizes the expected detectability of the post-merger part of the GW spectrum during a BNS merger, for different




***Figur 4:*** Rescaled dominant post-merger gravitational-wave frequency $f_{peak}/M_{tot}$ as function of the radius $R_{1.6}$ of a nonrotating neutron star with a gravitational mass of 1.6$M_{\odot}$ for different equations of state and different total binary masses and a mass ratio of unity. Figure reproduced from Bauswein & Stergioulas (2015).




***Figur 5:*** Mass-radius relations for EOSs LS375 and TMA. Error bars at 1.6 $M_{\odot}$ indicate the maximum deviation of the estimated radius inferred from a single GW detection of a low-mass binary NS merger (the two EOSs cannot be distinguished). The shaded boxes illustrate the maximum deviation of the estimated properties of the maximum-mass configuration, based on an extrapolation procedure that only uses detections of low-mass binary NS mergers. The two EOSs can be clearly distinguished. Figure reproduced from Bauswein, Stergioulas & Janka (2014).

| Instrument | $SNR_{full}$ | $D_{hor}$ (Mpc) | $\dot{N}_{det}$ (year$^{-1}$) |
|---|---|---|---|
| aLIGO | $2.99^{3.86}_{2.37}$ | $29.89^{38.57}_{23.76}$ | $0.01^{0.03}_{0.01}$ |
| A+ | $7.89^{10.16}_{6.25}$ | $78.89^{101.67}_{62.52}$ | $0.13^{0.20}_{0.10}$ |
| LV | $14.06^{18.13}_{11.16}$ | $140.56^{181.29}_{111.60}$ | $0.41^{0.88}_{0.21}$ |
| ET-D | $26.65^{34.28}_{20.81}$ | $266.52^{342.80}_{208.06}$ | $2.81^{5.98}_{1.33}$ |
| CE | $41.50^{53.52}_{32.99}$ | $414.62^{535.221}_{329.88}$ | $10.59^{22.78}_{5.33}$ |

***Table 1:*** Expected detectability of the post-merger part of the GW spectrum during a BNS merger. For various existing and proposed instruments, the second column shows the signal-to-noise ratio for the full waveform, $SNR_{full}$, for an optimally oriented source at 50 Mpc. The third column shows the expected horizon distance $D_{hor}$, assuming an optimal matched-filter SNR of 5. The last column shows the expected detection rate, based on the achieved horizon distance and assuming the realistic binary coalescence rate proposed in Abadie et al (2010). In all cases, the median across all simulated waveforms is shown, while superscripts and subscripts show the 10$^{th}$ and 90$^{th}$ percentiles, respectively. Table adapted from Clark et al. (2016).

existing and planned detectors. At a fixed distance of 50 Mpc the signal to noise ratio (SNR) of the full post-merger waveform for an optimally oriented source ranges between about 3 for the design sensitivity of Advanced LIGO (aLIGO) and about 40 for the proposed 3rd-generation LIGO Cosmic Explorer (CE). If one requires an SNR of 5 for detection, then the distance to which the post-merger phase can be detected (the horizon distance $D_{hor}$) ranges from about 30Mpc for aLIGO to about 400 Mpc for CE. Assuming the realistic neutron star binary coalescence rate proposed in Abadie et al (2010), this translates to an expected detection rate that is still low for aLIGO but becomes interesting with the planned LIGO Voyager (LV) upgrade (1 detection per 2.5 years of operation) and substantial with the proposed CE detector (10 detections per year).

Gravitational waves are thus a competitive new tool for measuring neutron star radii with unprecedented accuracy and revealing the high-density equation of state that describes their interiors.

## Planned Detectors:

**LIGO A+** (Miller et al. 2015, LIGO Scientific Collaboration 2015) will include a set of upgrades to the existing LIGO facilities, including frequency-dependent squeezed light, improved mirror coatings and potentially increased laser beam sizes. Noise amplitude spectral sensitivity would be improved by a factor of about 2.5-3 in the frequency range of 1-4 kHz. A+ could begin operation as early as 2017-18.

**LIGO Voyager** (*LV*) (LIGO Scientific Collaboration 2015) will be a major upgrade to the existing LIGO facilities, including higher laser power, changes to materials used for suspensions and mirror substrates and, possibly, low temperature operation. LV would become operational around 2027-28 and offer noise amplitude spectral sensitivity improvements of about 4.5-5 in the frequency range of 1-4 kHz.

**LIGO Cosmic Explorer** (*CE*) (LIGO Scientific Collaboration 2015) will be a new LIGO facility rather than an upgrade, with operation envisioned to commence after 2035, probably as part of a network with LV. CE would be a straightforward extrapolation of A+ or LV technology to a much longer arm length of 40 km, which would be up to 14 times more sensitive than aLIGO in the range of 1-4 kHz.

**Einstein Telescope** (*ET-D*) (Punturo et al. 2010, Hild et al. 2011) is the proposed European third-generation GW detector. In the ET-D configuration, two individual interferometers are envisioned, one with increased sensitivity at low frequencies and the other with increased sensitivity at high frequencies. Both interferometers will be of 10 km arm length and housed in an underground facility. The full observatory will consist of three such detectors in a triangle arrangement. ET-D is expected to be about 8 times more sensitive than aLIGO in the frequency range of 1-4 kHz.

## References


Aasi J et al (The LIGO Scientific Collaboration) 2015 Advanced LIGO *Class. Quantum Grav.* **32** 074001

Abadie J et al 2010 Topical review: predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors *Class. Quantum Grav.* **27** 173001

Abbott B P et al (The LIGO Scientific Collaboration and Virgo Collaboration) 2016 *Phys. Rev. Lett.* **116** 061102

Acernese F et al 2015 Advanced Virgo: a second-generation interferometric gravitational wave detector *Class. Quantum Grav.* **32** 024001

Andersson, N. and Kokkotas, K. D. 1998 Towards gravitational wave asteroseismology, *Mon. Not. R. Astron. Soc.* **200**, 1059-1068

Aso Y, Michimura Y, Somiya K, Ando M, Miyakawa O, Sekiguchi T, Tatsumi D and Yamamoto H 2013 Interferometer design of the KAGRA gravitational wave detector *Phys. Rev. D* **88** 043007

Bauswein A and Janka H-T 2012 Measuring neutron-star properties via gravitational waves from neutron-star mergers *Phys. Rev. Lett.* **108** 011101

Bauswein A, Janka H-T, Hebeler K and Schwenk A 2012 Equation-of-state dependence of the gravitational-wave signal from the ring-down phase of neutron-star mergers *Phys. Rev. D* **86** 063001

Bauswein A and Stergioulas N 2015 Unified picture of the post-merger dynamics and gravitational wave emission in neutron star mergers *Phys. Rev. D* **91** 124056

Bauswein A, Stergioulas N and Janka H-T 2014 Revealing the high-density equation of state through binary neutron star mergers *Phys. Rev. D* **90** 023002

Bauswein A, Stergioulas N and Janka H-T 2015 Exploring properties of high-density matter through remnants of neutron-star mergers *Eur. Phys. J. A* **52** 56

Bernuzzi S, Nagar A, Thierfelder M and Brügmann B 2012 Tidal effects in binary neutron star coalescence *Phys. Rev. D* **86** 044030

Clark J, Bauswein A, Cadonati L, Janka H-T, Pankow C and Stergioulas N 2014 Prospects for high frequency burst searches following binary neutron star coalescence with advanced gravitational wave detectors *Phys. Rev. D* **90** 062004

Clark J A, Bauswein A, Stergioulas N and Shoemaker D 2016 Observing gravitational waves from the post-merger phase of binary neutron star coalescence *Class. Quantum Grav.* **33** 085003

Damour T, Nagar A and Villain L 2012 Measurability of the tidal polarizability of neutron stars in late-inspiral gravitational-wave signals *Phys. Rev. D* **85** 123007

Doneva D and Kokkotas K D 2015 Asteroseismology of rapidly rotating neutron stars - an alternative approach *Phys. Rev. D* **92** 124004

Duez M D 2010 Numerical relativity confronts compact neutron star binaries: a review and status report *Class. Quantum Grav.* **27** 114002

Flanagan É É and Hinderer T 2008 Constraining neutron-star tidal Love numbers with gravitational-wave detectors *Phys. Rev. D* **77** 021502

Hild S et al 2011 Sensitivity studies for third-generation gravitational wave observatories *Class. Quantum Grav.* **28** 094013

LIGO Scientific Collaboration 2015 Instrument Science White Paper (LIGO-T1500290) https://dcc.ligo.org/LIGO-T1500290

Miller J, Barsotti L, Vitale S, Fritschel P, Evans M and Sigg D 2015 Prospects for doubling the range of advanced LIGO *Phys. Rev. D* **91** 062005

Özel F. and Freire P. 2016 Masses, Radii, and Equation of State of Neutron Stars, eprint arXiv:1603.02698

Punturo M et al 2010 The third generation of gravitational wave observatories and their science reach *Class. Quantum Grav.* **27** 084007

Read J S, Markakis C, Shibata M, Uryū K, Creighton J D E and Friedman J L 2009 Measuring the neutron star equation of state with gravitational wave observations *Phys. Rev. D* **79** 124033

Shibata M 2005 Constraining nuclear equations of state using gravitational waves from hypermassive neutron stars *Phys. Rev. Lett.* **94** 201101

Stergioulas N, Bauswein A, Zagkouris K and Janka H-T 2011 Gravitational waves and non- axisymmetric oscillation modes in mergers of compact object binaries *Mon. Not. R. Astron. Soc.* **418** 427-36

# RoboPol: Unveiling the Physics of Blazar Jets from Skinakas

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## Abstract:

*Blazars are powered by relativistic jets and radiate exclusively through extreme, non-thermal particle interactions, energized by accretion onto supermassive black holes. Despite intensive observational and theoretical efforts over the last four decades, the details of blazar astrophysics remain elusive. The launch of NASA's Fermi Gamma-ray Space Telescope in 2008 provided an unprecedented opportunity for the systematic study of blazar jets and has prompted large-scale blazar monitoring efforts across wavelengths. In such a multi-wavelength campaign, a novel effect was discovered: fast changes in the optical polarization during gamma-ray flares. Optical emission from blazars is significantly polarized and the polarization probes the magnetic field structure in the jet. For this reason, such polarization rotations reveal important information about the evolution of disturbances responsible for blazar flares. The RoboPol program for the polarimetric monitoring of statistically complete samples of blazars was developed in 2013 to systematically study this class of events. RoboPol is a collaboration between the University of Crete, Caltech, the Max-Planck Institute for Radio Astronomy, the Inter-University Centre for Astronomy and Astrophysics in India, and the Nicolaus Copernicus University in Poland. Using a novel polarimeter operating at the 1.3m telescope of the Skinakas Observatory in Crete, it has succeeded in its 3 years of operation in taking optopolarimetric rotations of blazars from novelty status to a well-studied phenomenon that can be used to answer long-standing questions in our theoretical understanding of jets. We review the RoboPol program and its most important results in the classification of the optopolarimetric properties of blazars, the statistical properties of polarization rotations, and their relation to gamma-ray activity in blazar jets.*

## 1. Physics of Blazars

Blazars are the most active galaxies known. The blazar phenomenon is believed to be the observable end-result of the non-thermal radiation from a relativistic jet, which is powered by an accreting supermassive black hole and is directed at a small angle with respect to our line of sight[1]. For this reason, blazars are an ideal laboratory to study the cosmic growth of black holes, the physics of accretion and the launching of relativistic jets, the formation and propagation of disturbances and shocks along these jets, and the acceleration of non-thermal particle populations to very-high energies (at least $10^8$–$10^{14}$ eV, and possibly up to $10^{21}$ eV, an energy comparable to the kinetic energy of an aggressively served tennis ball, carried by a single subatomic particle).

Blazar jets are observed almost exactly down their axis (see Fig. 1). For this reason, the observed properties of blazars are strongly affected by relativistic effects. Because of the bulk relativistic motion of the jet, blazar emission is strongly *beamed* in the forward direction of jet motion. Because of the favourable orientation of the jet with respect to our line of sight, the result of this beaming is that blazar emission is relativistically *boosted*, making the observed properties of blazars akin to nature's fireworks: their apparent luminosities are highly enhanced, their variability is strong and fast, and their jets feature apparently superluminal motions and emission across the electromagnetic spectrum, from radio to gamma-ray frequencies.

The potential of blazars to test our understanding of particle astrophysics and jet launching mechanisms provides a strong motivation for both observa-

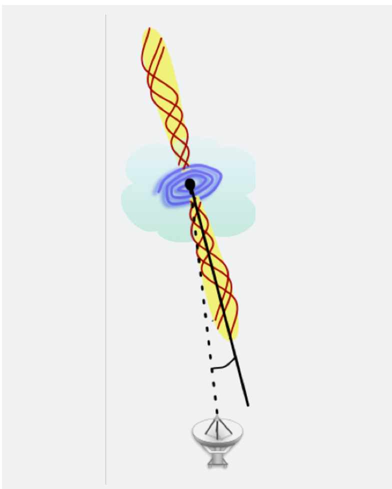


***Figure 1:*** Cartoon depiction of a basic physical model of a blazar. A relativistic jet is launched by a supermassive black hole. The power that sustains the jet is generated through accretion of matter onto the black hole (accretion disk depicted in blue) and/or extraction of rotational energy from the black hole itself. Here the jet is shown to be confined by a helical magnetic field (depicted in red). The jet is observed from Earth at a small angle relative to its axis. Only the half of the jet that is moving toward us is visible; the receding half is beamed away from us, which renders it practically invisible (very faint).

tional and theoretical studies of these intriguing objects. However, in spite of intensive observational and theoretical investigations over the last four decades, the details of the structure and composition of blazar jets, and of the mechanisms through which jets are launched and collimated, accelerate non-thermal particle populations, and emit radiation, remain elusive. The primary reason is that the same relativistic effects that make blazars interesting generate unique challenges for their study.

### 1.1 Observational Challenges

***Beaming:*** The amount of relativistic beaming of blazar emission is very sensitive to the angle between the jet axis and the line of sight. Even small variations in this angle induce large changes in the amount of beaming, thus resulting in significant variations in all observable quantities: apparent luminosity, variability timescales, apparent velocities of jet components, energy spectra). This effect in turn limits the repeatability of blazar behaviour, and it induces large scatter in possible correlations between observables and physical properties of blazar jets.

***Variability:*** Blazars are strongly variable on all timescales, and this property presents an additional observational complication in blazar studies. Because of irregular variability, the properties of blazar populations cannot be straightforwardly determined through single-epoch surveys alone, since these only capture a single snapshot of each source. Instead, blazars also need to be studied in the time domain.

***Lack of spatial resolution***: At most frequencies, blazar emission is spatially unresolved. As a result, and due to the close alignment between jet axis and line of sight, the received emission is an accumulation of photons from different locations along the jet. The location of the emission region in each frequency cannot therefore be directly determined through imaging; rather, it needs to be pinpointed by the combined analysis of a variety of observations (for example, by measuring time lags between flares at different frequencies) and by modelling.

### 1.2 Theoretical Challenges

From the theoretical perspective, although considerable progress has been achieved in the modelling of jet launching[2], particle acceleration, and non-thermal emission[3], degeneracies between the predictions of different models have slowed progress in model rejection and discrimination. For example, multiwavelength spectral modelling of blazars involves a large number of free parameters, and as a result physically different models can be tuned to fit the same datasets. Characteristic examples include the composition of the jet and the primary emission mechanism in gamma rays. Jets may be composed of an ion-electron plasma, accelerating both electrons and protons to very high energies, and the high energy emission could be due to proton interactions or proton-induced cascades (hadronic emission models). Alternatively, jets could be composed of an electron-positron plasma, in which case the accelerated particles are exclusively leptons, and the high-energy emission is due to inverse Compton scattering of soft photons to gamma-ray energies (leptonic emission models). Population models of blazars (luminosity functions, relation between spectra and luminosities, spectral index distributions) also suffer from considerable systematic uncertainties and have been long debated in the field.

As a result, to this day there is no unique, accepted model or mechanism for: (i) the acceleration of the jets near the inner parts of the accretion disk; (ii) the composition of the jets; (iii) jet confinement; and (iv) particle acceleration and magnetic field production, and consequently non-thermal emission.

### 1.3 Blazar observations in the Fermi era

Blazars are the most numerous population of sources in the gamma-ray sky. For this reason, the launch of NASA's *Fermi* Gamma-ray Space Telescope in June of 2008 provided an exceptional opportunity for the systematic study of blazar jets. The Large Area Telescope[4] (LAT) onboard Fermi observes the sky at energies between 100 MeV and a few hundred GeV with unprecedented sensitivity. In this energy range, relativistic particles can be probed through their leptonic emission in the case of electron/positron jets[5], or a combination of hadronic emission from primaries and leptonic emission from cascade-produced leptonic secondaries in the case of hadronic jets[6]. The LAT operates in continuous sky-scanning mode, and this observing strategy, in combination with its very large (1/5 of the sky) field of view, allows it to complete one pass of the entire sky every three hours. In this way, the LAT is able to provide continuous variability information for the entire detectable blazar population, on timescales dependent on the blazar brightness (long enough to allow the detection of the blazar over the diffuse background, down to a few hours for the brightest objects).

The operation of *Fermi* LAT has additionally prompted very significant efforts in multi-wavelength and multi-technique blazar monitoring. The Caltech Radioastronomy group leads a monitoring program of unprecedented sample size, which observes over 1,800 northern blazars twice every week at a single frequency (15 GHz) with the 40 m telescope at the Owens Valley Radio Observatory[7]. At the same time, the VLBI group of the Max-Planck-Insitut für Radioastronomie in Bonn operates the F-GAMMA program,[8] a monitoring effort that follows, on a monthly timescale, the broad-band spectra of about 60 selected *Fermi* active galactic nuclei. Coverage of flaring events or support for otherwise triggered multiwavelength campaigns and/or monitoring of smaller blazar samples is also provided in intermediate frequencies, e.g. by Whole Earth Blazar Telescope[9] in optical and near-infrared; by Swift-UVOT[10] in optical and UV; and by Swift-XRT[11], Swift-BAT[12], RXTE[13] and INTEGRAL[14] in X-rays. Additionally, the Higashi-Hiroshima Observatory[15] and the University of Arizona[16] each maintains an optical polarization monitoring program in support of Fermi. The MOJAVE program[17] provides VLBI monitoring of ~200 blazars, providing valuable information on core fluxes at 15 GHz, and on superluminal velocities of jet components, which probe the jet Lorentz factors. And the RoboPol program, presented in this review, follows the optopolarimetric properties of ~ 100 blazars (both unbiased samples for statistical studies as well as sources of high individual interest) with weekly or better cadence.

### 1.4 Optical Polarization in Blazars

While the nature of the high-energy emission in blazars is actively debated and is likely to differ between different sources, optical emission is generally accepted to be synchrotron emission from relativistic electrons. As such, the optical emission is both expected and observed to be significantly linearly polarized, with the degree of polarization depending on the number of regions contributing to the total observed emission and the uniformity of the magnetic field within each region. Polarization measurements of blazar synchrotron emission can thus reveal the structure of the magnetic field in the emission region. Polarization variability, on the other hand, can be used to locate the emission region in the jet as well as track the evolution of flaring events within the jet.

That blazar optical emission is polarized and that the polarization varies is a long-standing result[18]. However, the polarization variability was generally observed to be erratic and it was not clear that it could be used in a straightforward manner to gather independent information regarding the evolution of flaring events. This view, however, changed radically with the discovery of long, monotonic variations of the optical polarization angle occurring concurrently with gamma-ray activity.

### 1.5 Fast Optical-Polarization Changes During Gamma-ray Flares: a Novel Phenomenon Discovered in the Fermi Era

A multi-wavelength campaign triggered by Fermi observations of blazar 3C279 and which included measurements of the blazar's optical brightness and polarization made a remarkable serendipitous discovery: the polarization angle of optical photons from 3C279 exhibited an almost 180-degree-angle rotation during a gamma-ray flare recorded by Fermi[19]. At the same time, the degree of polarization dropped from 30% to 10% during the flare, only to recover shortly after the source returned to pre-flare activity levels. Similar polarization-rotation events were observed in PKS 1510−089[20], and in BL Lac[21].

The discovery of the new class of polarization rotation events coupled with gamma-ray activity prompted a series of theoretical modelling efforts aiming to explain the behaviour of the degree and angle of the optical polarization during flares.

Proposed interpretations for the flares in 3C 279, PKS 1510−089 and BL Lac included magnetic field distributions that deviate from axisymmetry, a swing of the jet with respect to the line of sight, or the propagation of the emitting disturbance along a helical path in a magnetically dominated jet[18,19,20]. However, further progress was hindered by the lack of information regarding the frequency and repeatability of such events. It was not known whether these events represented typical behaviour in all blazars, typical behaviour in some blazars, or whether they were extraordinary events associated with only a special type of flare even within a single source. In addition, it was not clear whether the association of polarization rotations with gamma-ray activity represented a true causal relationship or a coincidental association, because of increased optopolarimetric data gathering during periods of known gamma-ray flaring.

Optical polarization rotation events were thus a "novelty" class of events, in dire need of systematic exploration. This problem could be overcome only with a systematic search for rotation events in a large number of blazars; a statistical assessment of the fraction of gamma-ray flares that were are associated with changes in polarization fraction and angle, and vice versa; and high-cadence monitoring of the manner in which they unfold across the electromagnetic spectrum. The RoboPol program was developed to provide this missing link, by conducting blazar optical linear polarization monitoring of unprecedented scale and cadence.

## 2. RoboPol: A Systematic Study of Fast Optical-Polarization Changes in Blazar Jets

In spite of the tremendous importance of events such as the one observed during the flare of 3C 279 in constraining theoretical blazar models, the rate at which new events of this type were likely to be discovered with optopolarimetric monitoring programs that were in operation before RoboPol was expected to be very low: these programs followed only a small numbers of sources, and were aimed at the way optical polarization varied over long timescales, rather than at the fast-changing rotation events.

To remedy this, an international collaboration between the University of Crete and FORTH in Greece, the California Institute of Technology in the United States, the Max-Planck Institute for Radioastronomy in Bonn, Germany, the Nicolaus Copernicus University in Poland, and the Inter-University Centre for Astronomy and Astrophysics (IUCAA) in India developed RoboPol: a new blazar monitoring campaign, specifically aimed at measuring and characterizing the optical polarization behavior of blazars during flares.

RoboPol was designed to improve simultaneously on all aspects of optopolarimetric blazar monitoring: it employed an innovative, high-accuracy and high-sensitivity polarimeter, designed specifically for the program; it followed a large, carefully selected, unbiased, statistically complete sample of blazars, built through strict, quantitative and reproducible criteria; and it devoted an unprecedented amount of observing time to the optopolarimetric study of blazars, in order to achieve the observing cadence necessary for the systematic study of rotatio events.

The RoboPol program employs an innovative, cutting-edge optical polarimeter, especially designed and built for the program, deployed in May 2013 at the 1.3m telescope of the Skinakas Observatory in Crete. Unlike conventional astronomical polarimeters, RoboPol (see Fig. 2) was designed without any mov-

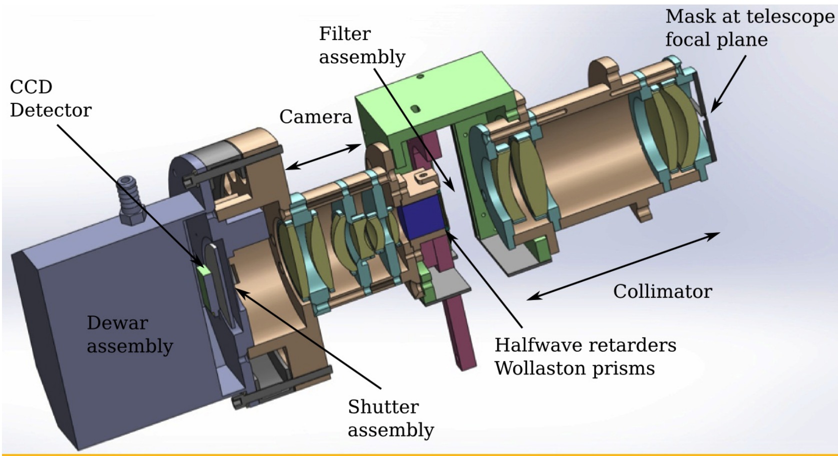



***Figure 2:*** Schematic design of the innovative RoboPol polarimeter

ing parts. Its innovative design allows it to obtain *simultaneously* measurements of both fractional Stokes parameters q = Q/I and u = U/I, bypassing the need for multiple exposures and avoiding unmeasurable systematic uncertainties that might be induced due to sky changes between measurements and imperfect alignment of rotating optical elements. The instrument has a large field of view (13′×13′) and thus relative photometry is possible using standard catalog sources. The large field of view can also be used (and has been used) for the rapid polarimetric mapping of large sky areas (see for example the RoboPol mapping of the Polaris Flare molecular cloud[22].

The program is operated at the Skinakas Observatory (http://www.skinakas.org.gr), a joint facility of the University of Crete and the Foundation for Research and Technology – Hellas. The Observatory at Skinakas, a 1750m peak just 50km west of the city of Heraklion on the island of Crete, has been operated since 1986. Its location displays the best atmospheric conditions for astronomical observations in Europe, comparable to several of the largest facilities in the world (median seeing of 0.7 arcsec[23]). The main 1.3m Ritchey-Chretien telescope has sensitive detectors more than capable of providing accurate light curves of blazars[24] over long periods, due to the excellent weather conditions on the island of Crete for most of the year. The Skinakas Observatory committed four nights per week, on average, over the entire Skinakas observing season (May-November each year), for three years (2013-2015).

## 3. Main RoboPol Results

The first three seasons of the RoboPol program consisted of one single-epoch polarization survey of 104 gamma-ray–loud and gamma-ray–quiet sources during the 2013 season, and monitoring of gamma-ray–loud and gamma-ray–quiet unbiased samples of sources during the next two (2014 and 2015) observing seasons (61 during the first season, including 51 gamma-ray–loud and 10 gamma-ray–quiet).

In this section, we summarize the most important results of RoboPol to date on optopolarimetric rotations of blazars and their relation to gamma-ray activity in blazars. The results summarized below are based on the single-epoch polarization survey and the first two seasons of RoboPol blazar monitoring.

The RoboPol program defines as a "polarization rotation" a monotonic change of the polarization angle that consists of at least four measurements with significant polarization angle changes between them and that is at least 90° long. The 180° ambiguity in the measurement of polarization angle is resolved by demanding the change between two consecutive polarization angle measurements be minimal.

Before RoboPol, 17 rotations were known that were consistent with the above criteria. During its first two seasons, RoboPol detected 27 additional optical polarization rotations (16 in the first season, and 11 in the second).

### 3.1 Gamma-ray–loud blazars are more polarized than gamma-ray–quiet blazars

In the single-epoch polarization survey that was performed before the monitoring program begun, the polarization fractions of two samples of blazars (gamma-ray–loud and gamma-way–quiet) were measured and their distributions were compared. It was found[25] that the hypothesis that the two distributions are the same is rejected at a 3σ confidence level (see Fig. 3). Instead, *the average polarization fraction of gamma-ray–loud blazars was found to be twice that of gamma-ray–quiet blazars*.

The result is confirmed if, instead of the single-epoch survey, average polarization fractions over the monitoring period are used[26]. In this way, a direct link between optical polarization and gamma-ray loudness has been established.

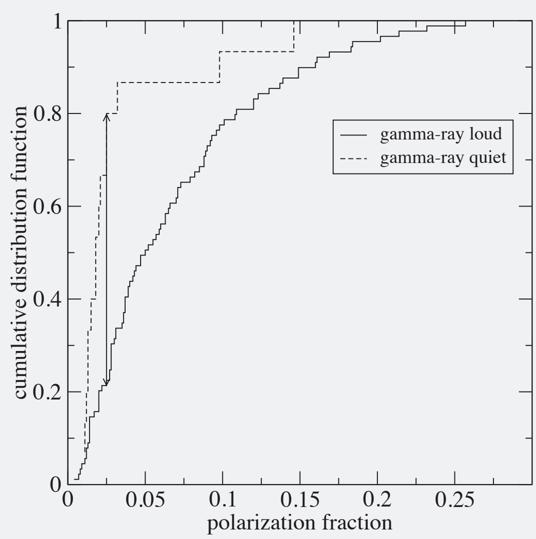
It is also interesting to note that no rotation has been detected to date by RoboPol in a gamma-ray–quiet blazar.

### 3.2 At least some polarization rotations are physically connected to gamma-ray activity

At the onset of the RoboPol program, it was not clear whether the connection between gamma-ray activity and optical polarization rotations is direct and causal, or coincidental. It seemed in principle possible that, because optopolarimetric monitoring of sources before RoboPol was intensified during gamma-ray activity, rotations were preferentially detected during gamma-ray flares without really being more frequent during periods of increased gamma-ray emission. RoboPol data enabled testing of this scenario, because RoboPol sources were monitored regardless of their gamma-ray activity.

RoboPol first-season data were used to perform this test. Since Fermi is continuously monitoring the entire sky, it is possible to generate very long gamma-ray light curves (since the launch of Fermi) for all gamma-ray–loud blazars that have ever exhibited rotations. For each blazar that exhibited one or more rotations, all gamma-ray flares were identified in their long-term lightcurves, and then the rotations were randomly placed at some time slot in the gamma-ray–lightcurve, and the time lag between rotation and the closest in time gamma-ray flare was calculated. This process was repeated a million times for the entire set of rotating blazars. Only one in

***Figure 3:*** Cumulative distribution function of polarization fractions for gamma-ray–quiet (dashed line) and gamma-ray–loud (solid line) blazars. Data from Pavlidou et al. 2014.



5,000 such simulations produced a distribution of timelags that were overall closer to zero than the actual data. The conclusion was[27] that it is very unlikely (probability $2\times10^{-4}$) for the entire set of rotations to be accidentally close to gamma-ray activity: most rotating blazars do not flare that often in gamma rays, so "accidentally" having all RoboPol-measured rotations land in time as nearby a gamma-ray-flare as we see in the data is not likely.

### 3.3 The brightest gamma-ray flares have optical polarization rotations occurring soon before or shortly after

Using first-season monitoring data, the relationship between the relative amplitude of gamma-ray flares and the time lag between a polarization rotation and the nearest in time flare was explored[27]. The relative amplitude of the gamma-ray flare was defined as the ratio between the amplitude of the flare (maximum flare flux minus the constant underlying flux) and the average gamma-ray flux of the blazar. It was found (see Fig. 4) that for flares of relative amplitude higher than a factor of five, the average (redshift-corrected) time lag between rotation and flare is four times lower (~5 days vs ~20 days) compared to the average time lag between lower-relative-amplitude flares and rotations. However, the exact significance of this result is not easy to assess, due to the still-low statistics and the relatively large error bars in the time-lag estimation, dominated by cases where sparse data make it hard to identify the beginning or the end of a rotation.

This result is consistent with the notion that there may exist more than one class of rotations: rotations that are indeed physically coherent events, and rotations that are results of a "random walk" in polarization angle, and are only coincidentally monotonically changing over a long period of time.

Simulations of a simple "random walk" model showed that while many of individual RoboPol rotations may indeed be a result of a random walk, it is very unlikely that the entire set of RoboPol rotations were generated by random walks, again pointing towards the possibility of more than one class of rotations.

### 3.4 There is a "rotator" class of blazars

The overall polarization properties of blazars in the monitored sample during the first observing period were used to explore whether blazars with observed rotations are dissimilar to blazars where no rotation was recorded, or whether the two populations are otherwise similar. The latter result would imply that all blazars may be capable of producing rotations if they were observed for long enough.

It was found that blazars with detected rotations were indeed different from blazars where no rotation had ever been detected. Blazars with detected rotations change their polarization angle at a higher rate overall (not only during rotations), while they show consistently longer monotonic polarization angle changes, even if rotations are excluded. These results are statistically significant[27], and indicate that there is a distinct "rotator" class among gamma-ray–loud blazars. Many blazars may not ever show a rotation, regardless of how long they are observed.

### 3.5 The polarization fraction typically decreases during rotations

Using rotations of the first two seasons[28], the behaviour of the polarization fraction during rotations and during other periods was explored. It was found (see Fig. 5) that it is possible for the polarization to either increase or decrease during rotations; however, more blazars appear to have a lower polarization fraction during rotations than vice versa.

## 4. Outlook

In its three years of operation, RoboPol has succeeded in transforming optopolarimetric rotations of blazars from novelty status to a well-studied phenomenon that can be used to answer long-standing questions in our theoretical understanding of jets. An unambiguous connection between gamma-ray emission and optical polarization has been established, and the exact nature of the relationship (whether causal or connected with a common driver) can now be investigated using detailed modelling. A new class of blazars ("rotators") has been identified, and it has been established that at least some optical polarization rotations are physically coherent events, connected with gamma-ray flaring. Systematic trends in rotation properties have been identified, includ-

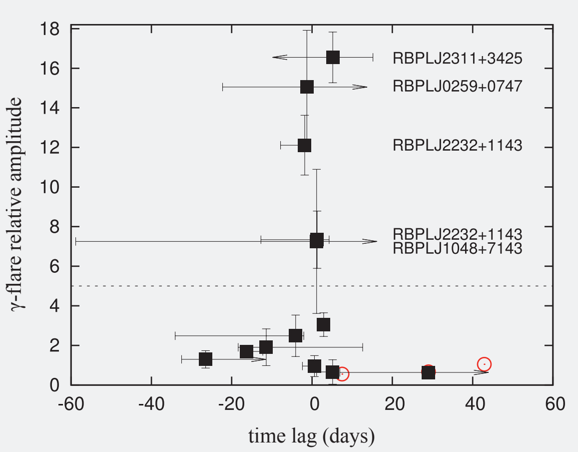



***Figure 4:*** Relative gamma-ray flare amplitude versus time lag between gamma-ray flare and rotation. Open red circles indicate lags that have not been redshift-corrected because the redshift of the source is not known (data from Blinov et al. 2015).

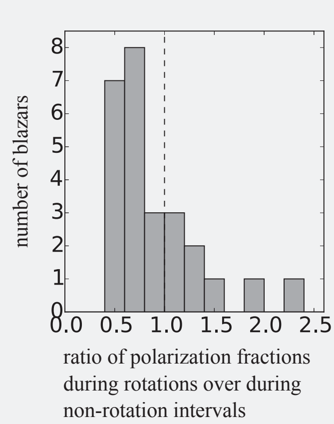



***Figure 5:*** Histogram of polarization fraction ratio between rotating and non-rotating periods in different blazars.

ing that the polarization fraction tends to drop during rotations.

In addition, RoboPol monitoring has produced an unprecedented database of optopolarimetric observations that is certain to be explored and used by the astrophysical community in many more ways in the coming years.

During the current Skinakas observing season, RoboPol is pursuing even higher cadence observations of a selected sub-sample of established rotators that are going to be observed more frequently than ever before. This ultra-high-cadence program will open for the first time the window of fast rotations and will allow us to gain new insight on the frequency of occurrence of such events.

Besides these fundamental contributions to our understanding of blazar physics, RoboPol has yielded important results in a variety of other astrophysical systems, including interstellar clouds[22], gamma-ray–bursts[29], and X-ray binaries[30].

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## References

1. Blandford & Konigl 1979, *ApJ*, **232**, 34
2. e.g., Blandford & Znajek 1977, *MNRAS* **179**, 433; Blandford & Payne 1982, *MNRAS*, **199**, 883; Vlahakis, & Tsinganos, 1999, *MNRAS* **307**, 279; Vlahakis & Konigl 2004, *ApJ*, **605**, 656; McKinney & Blandford 2009, *MNRAS* **394**, L126
3. e.g, Dermer, Schlickeiser, & Mastichiadis, 1992, *A&A* **256**, L27; Mannheim 1993, *A&A.*, **269**, 67, Sikora, Begelman & Rees 1994, *ApJ*, **421**, 153; Blandford & Levinson 1995, *ApJ*, **441**, 79; Krawczynski, Coppi & Aharonian 2002, *MNRAS* **336**, 721; Böttcher & Reimer 2004, *ApJ*, **609**, 576; Ghisellini et al. 2011, *MNRAS*, **411**, 901; Nalewajko, Giannios, Begelman, Uzdensky & Sikora 2011, *MNRAS*, **188**
4. Atwood et al. 2009, *ApJ*, **697**, 1071
5. e.g. Dermer, Schlickeiser, & Mastichiadis, 1992, *A&A* **256**, L27; Sikora, Begelman & Rees 1994, *ApJ*, **421**, 153; Blandford & Levinson 1995, *ApJ*, **441**, 79
6. e.g. Mannheim 1993, *A&A.*, **269**, 67
7. http://www.astro.caltech.edu/ovroblazars/
8. http://www.mpifr-bonn.mpg.de/div/vlbi/fgamma/fgamma.html
9. http://www.oato.inaf.it/blazars/webt/gasp/homepage.html
10. http://www.swift.psu.edu/uvot/
11. http://www.swift.psu.edu/xrt/
12. http://heasarc.gsfc.nasa.gov/docs/swift/about_swift/bat_desc.html
13. http://heasarc.nasa.gov/docs/xte/xtegof.html
14. http://www.sciops.esa.int/index.php?project=INTEGRAL&page=index
15. Uemura et al. 2008, Proceedings of the Workshop on "Blazar Variability across the Electromagnetic Spectrum"
16. http://james.as.arizona.edu/~psmith/Fermi/DATA/data.html
17. https://www.physics.purdue.edu/astro/mojave/
18. Kinman et al. 1966, *ApJ*, **146**, 964
19. Abdo et al. 2010, *Nature*, **463**, 919
20. Marscher et al. 2010, *ApJL*, **710**, 126
21. Marscher et al. 2008, *Nature*, **452**, 966
22. Panopoulou et al. 2015, *MNRAS*, **452**, 715
23. Boumis, Steiakaki, Mavromatakis, Paterakis & Papamastorakis 2001, arXiv:astro-ph/0111022.
24. e.g. Papadakis, Samaritakis, Boumis & Papamastorakis, 2004, *A&A*, **426**, 437
25. Pavlidou et al. 2014, *MNRAS*, **442**, 1693
26. Angelakis et al. (2016), *MNRAS* submitted
27. Blinov et al. 2015, *MNRAS*, **453**,1669
28. Blinov et al. 2016, *MNRAS*, **457**, 2252
29. King et al. 2014, *MNRAS*, **445**, L114
30. Reig et al. 2014, *MNRAS*, **445**, 4235

# Coronal Mass Ejections: From Sun to Earth

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## Abstract:

*Coronal Mass Ejections (CMEs) are gigantic expulsions of magnetized plasmas from the solar corona into the interplanetary (IP) space. CMEs spawn ~ $10^{15}$ gr of mass and reach speeds ranging between several hundred to a few thousand km/s (e.g., Gopalswamy et al. 2009; Vourlidas et al. 2010). It takes 1-5 days for a CME to reach Earth. CMEs are one of the most energetic eruptive manifestations in the solar system and are major drivers of space weather via their magnetic fields and energetic particles, which are accelerated by CME-driven shocks. In this review we give a short account of recent, mainly observational, results on CMEs from the STEREO and SDO missions which include the nature of their pre-eruptive and eruptive configurations and the CME propagation from Sun to Earth. We conclude with a discussion of the exciting capabilities in CME studies that will soon become available from new solar and heliospheric instrumentation.*

## Flux-rope CMEs: Nature or Nurture?

A major recent result in CME research is the recognition of their magnetic flux-rope nature when observed in coronographic fields of view, several solar radii (Rs) above the solar photosphere, (Vourlidas et al. 2013). A magnetic flux rope is a half-torus structure characterized by field lines wrapping around the torus major axis. Vourlidas et al. (2013) analyzed more than 10000 CMEs observed by the LASCO coronagraph of the Solar and Heliospheric Observatory (SOHO) mission and found that at least 40% exhibit clear flux rope signatures. Figure 1a shows an example of a flux-rope CME exhibiting the familiar 3-part morphology (bright core → prominence material collected at the bottom, concave-upward, part of the flux rope; dark cavity → flux rope; bright front → piled-up material). Fast enough CMEs to drive a shock, often exhibit a second, dimmer bright front around the CME's bright front, corresponding to the shock front (e.g., Ontiveros & Vourlidas 2009). MHD simulations of CMEs predict emission signatures of flux ropes which are cumbersome with the actual coronagraphic observations (Figure 1b). A magnetic flux rope configuration is also very commonly found when the interplanetary counterparts of CMEs (ICMEs) reach 1 AU and are detected in-situ from large-scale and smooth rotation of their magnetic fields, i.e., they exhibit a magnetic cloud topology (e.g., Burlaga et al. 1981). Magnetic clouds are found in at least ~ 40% of ICMEs at 1 AU (e.g, Jian et al. 2006).

While a flux-rope nature of CMEs-ICMEs is widely accepted when they reach coronagraphic fields of view, after the CME initiation, and further away in the IP space, it is currently far from settled whether a flux rope is present *before* the CME eruption or *it forms on the fly*. There exist CME initiation models which require a pre-

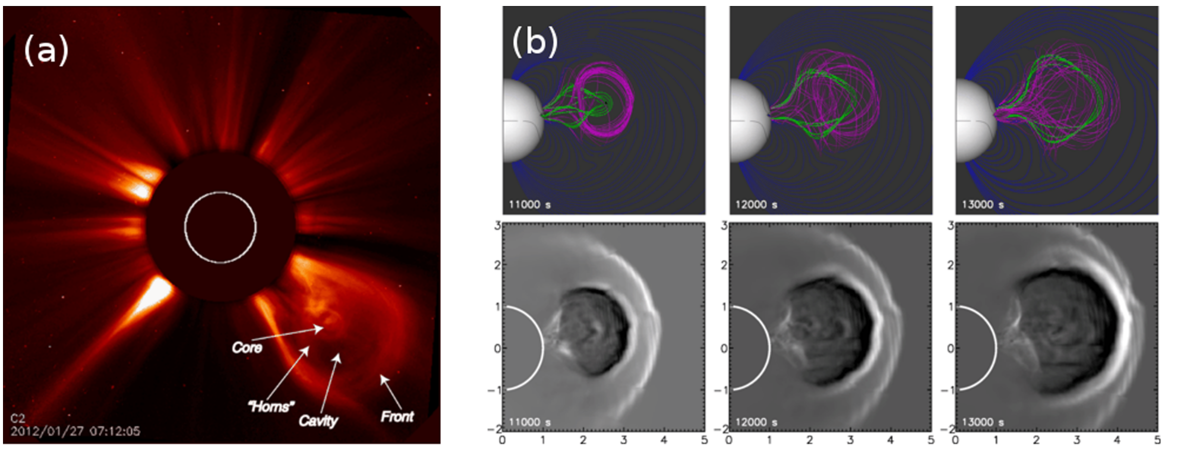


***Figure 1:*** Panel (a): 3-part view of a flux-rope CME observed by LASCO onboard SOHO. Panel (b): snapshots from an MHD CME simulation. The colored lines of the upper 3 panels correspond to magnetic field lines, with the purple lines corresponding to the flux rope and the blue ones to the ambient corona, while the bottom 3 panels correspond to the line-of sight integrations of the MHD model's density distribution which supplies proxies of synthetic coronagraph images. From Vourlidas et al. (2013).

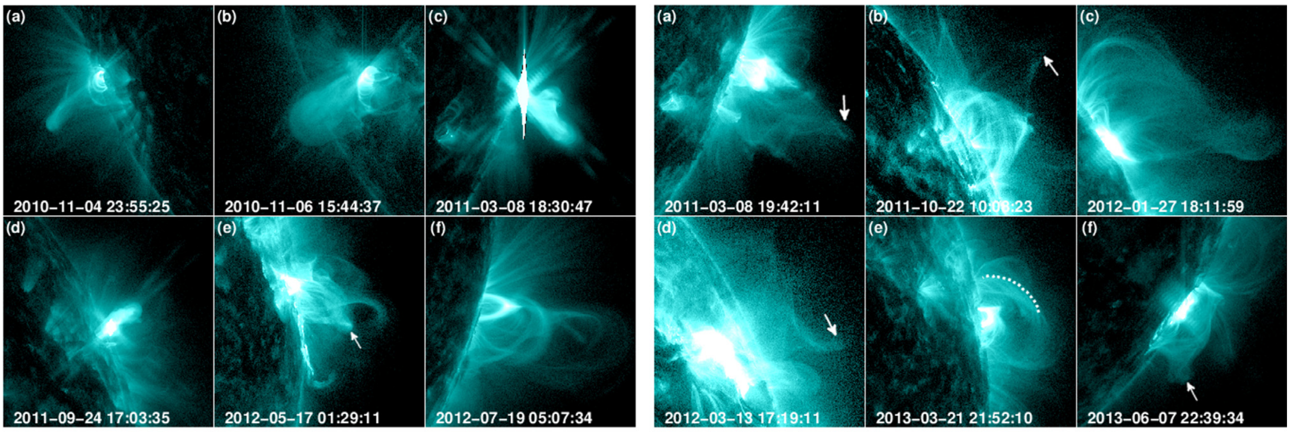


***Figure 2:*** Examples of hot flux ropes observed during big solar flares. The left six panels contain edge-on (i.e, along the flux-rope major axis) views and the right six panels contain face-on (i.e., across the flux-rope major axis) views. The observations were made in the 131 Å channel of a AIA on-board SDO which observes plasmas at ~ 10 MK. From Nindos et al. (2015).

eruptive flux rope (e.g., Kliem & Török, 2006) and others which do not (e.g., Antiochos et al. 1999, Lynch et al. 2008). Models of the latter class, have a sheared magnetic arcade (i.e., a set-up of loops running closely to the Polarity Inversion Line (PIL) of the photospheric magnetic field) as initial condition instead of a flux rope. Powerful flares/CMEs originate from strongly deformed PILs (e.g., Georgoulis & Rust 2007; Schrijver, 2007). A magnetic flux rope could form when a flux tube, twisted or not, emerges from the sub-photospheric convection zone into solar atmosphere and interacts (reconnects) with the ambient coronal magnetic field (e.g., Archontis & Török 2008; Fan 2009; Archontis et al. 2013; Leake et al. 2013; Leake et al. 2014; Syntelis et al. 2015), or when flux cancellation in sheared magnetic arcades takes place (e.g., van Ballegooijen & Martens 1989; Amari et al. 2000; Aulanier et al. 2010; Green et al. 2011; Fang et al. 2012; Savcheva et al. 2012; Amari et al. 2014). These magnetic field reconfigurations lead to significant plasma heating that is manifested by flaring activity that can be observed in emissions probing high-temperature plasmas.

Major advances in our understanding and characterization of the pre-eruptive configuration of CMEs were achieved thanks to the Solar Dynamics Observatory (SDO) mission launched in 2010. SDO is equipped with the Atmospheric Imaging Assembly (AIA) which supplies high spatial resolution(~ 0.6 arcsec) and cadence (12 s) images of the solar disk and the low corona in narrow-band EUV channels sensitive to hot (>5 MK) plasmas pertinent to flaring either confined (i.e., non-eruptive) or eruptive (i.e., associated with a CME). Since the bulk of the plasma in the ambient corona is significantly warmer, observations in these hot channels have significantly less line of sight confusion (the corona is optically thin in the EUV) which allows to more easily pick up structures illuminated by impulsive heating events associated with magnetic reconnection. Under coronal conditions, the plasma is frozen along the magnetic field lines and thus coronal imaging supplies a notion of the coronal magnetic field configuration. The AIA observations showed evidence of hot flux ropes in several case-studies of CME-initiation sequences (e.g., Cheng et al. 2011; Zhang et al. 2012; Cheng et al. 2014). Nindos et al. (2015) performed an extensive statistical survey of 141 limb events associated with big flares and found that 49 % of the associated to a CME flares showed clear evidence of a hot flux rope. Several examples of hot flux ropes are given in Figure 2. These observational inferences of flux ropes from imaging data are augmented by non-linear force-free extrapolations (e.g., Wiegelmann 2004) of the photospheric vector magnetic field, supplied by SDO's Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012), into the corona (e.g. Sun et al. 2012; Guo et al. 2013; Cheng et al. 2014). Reliable magnetic field extrapolations can be performed only relatively close to disk center. This is a setup which leads to more line of sight confusion and ambiguities in the interpretation of the EUV images as compared to limb views.

A common element of most of these AIA studies is that the hot flux ropes were first observed during or very close to the corresponding CME initiation, making it rather hard to decide whether these flux ropes were truly pre-eruptive. A limb observation of a truly pre-eruptive hot flux rope which was formed during a confined flare and erupted 7 hours later is reported in Patsourakos et al. (2013). Examples of on-disk hot flux-rope formation during confined flaring events, several hours before their eruption, along with arrangements of twisted magnetic field lines pertinent to flux ropes can be found in Chintzoglou et al. (2015); left panel of Figure 3. A key observational signature of flux-rope formation during confined flaring events is the conversion of mutual magnetic helicity to self magnetic helicity several hours before the onset of a major CME, signifying the resistive formation of helical field lines (Tziotziou et al. 2013; right panel of Figure 3). Magnetic helicity measures the degree of twist, writhe and linkage of the magnetic field and is an important factor in deciding the eruptivity of active regions (e.g., Nindos & Andrews 2004; LaBonte et al. 2007; Tziotziou et al. 2012).

## CME Propagation from Sun to Earth: kinematics, dynamics and modulations

The Solar and Terrestrial Relationships Observatory (STEREO) mission led to significant advances in our physical understanding and modeling of CME and ICME propagation and expansion. Since 2006, and the launch of STEREO, we have been able for the first time to continuously track and characterize in 3-dimensions (3D) CMEs, and related phenome-

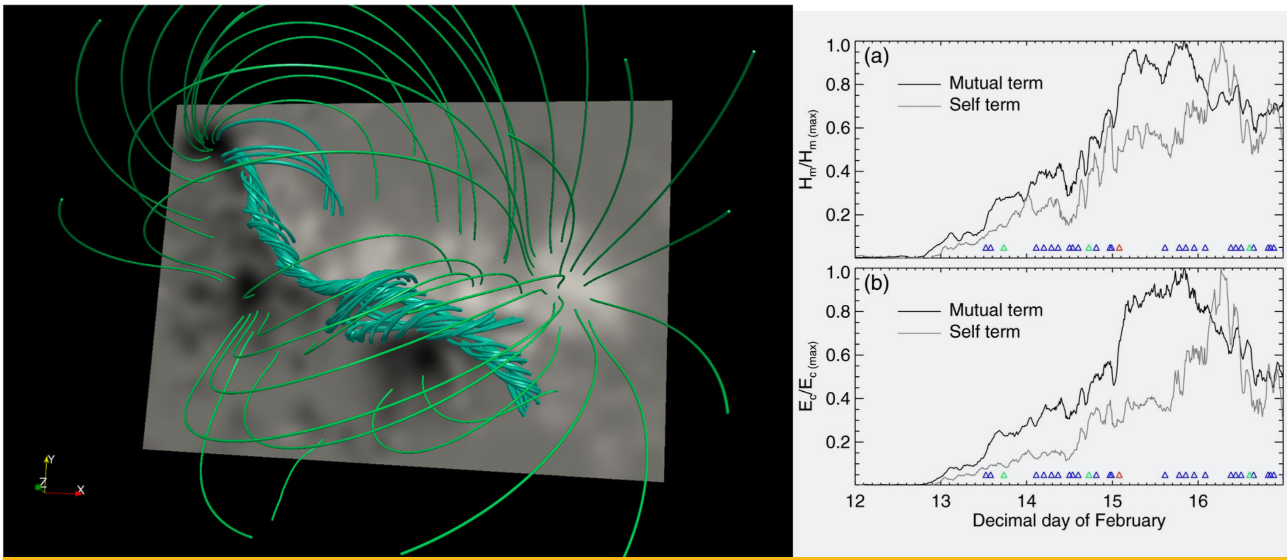


***Figure 3:*** Left panel. Example of a non-linear force-free magnetic field extrapolation over a solar active region using an HMI photospheric vector magnetogram as lower boundary condition. The grayscale map is the Bz component of the photospheric magnetic field. The colored tubes represent the extrapolated magnetic field, with teal corresponding to field lines with seed points in the region of the strong photospheric PIL showing evidence of twist, thus of flux rope structures, and with green to the overlying magnetic field lines. From Chintzoglou et al. (2015). Right panel. Temporal evolution of the magnetic helicity (upper plot) and of the free magnetic energy (lower plot) for an eruptive solar active region. Black (gray) lines correspond to mutual (self) terms. The self terms lag the mutual terms suggesting a progressive formation of helical (flux-rope) structures prior to the onset of a major CME. From Tziotziou et al. (2013).

na such as shocks and co-rotating interaction regions (regions of interaction between fast and slow solar wind streams), all way through from Sun to 1 AU. The STEREO mission consists of two spacecraft, with identical remote sensing and in-situ instrumentation, one moving slightly ahead (STA) and the other slightly behind (STB) Earth's orbit around the Sun, leading to a yearly separation rate of about 45 degrees between the two spacecraft, thereby offering simultaneous and stereoscopic views of the Sun, its corona and the inner heliosphere, from two distinct inner-heliospheric vantage points. These observations are achieved by the Sun Earth Coronal and Heliospheric Investigation (SECCHI; Howard et al. 2008) instrument package onboard STEREO. SECCHI is a set of EUV disk and low-corona imagers, white light coronagraphs and heliospheric imagers observing from disk center to 318 Rs. The dual-vantage point SECCHI observations, sometimes augmented by observations from a terrestrial (e.g., SDO) or L1 (SOHO) viewpoint, allowed us for the first time to deduce a set of important geometrical parameters of CMEs such as their "true" (heliocentric) distances, propagation directions, angular widths, rotation rates and shapes. Knowledge of these parameters is essential for both understanding CME propagation and evolution as well as for space weather purposes. For instance, it is important to know if a given CME is Earth-directed, and if yes, what will be its transit time to, and its speed and orientation at, 1 AU. ICME magnetic field and orientation at 1 AU are the chief parameters for determining their geoeffectiveness through the magnitude of the associated geomagnetic storms (e.g., Wu & Lepping 1996).

Prior to STEREO, our observational knowledge of the 3D structure and kinematics of CMEs, and of the solar corona and heliosphere in general, was limited to single viewpoint observations, allowing access to plane-of-sky properties only, given the optically-thin nature of the solar corona in the corresponding emissions. Such observations are fraught with significant uncertainties and ambiguities. For example, a single viewpoint observation gives access to the projected CME distance only and not to its true distance. In addition, CME rotation and angular expansion could not be unambiguously distinguished without multi-viewpoint observations (e.g., Vourlidas et al. 2011).

Two basic methods are used to obtain the 3D properties of CMEs: forward modeling and triangulation. Forward modeling (e.g., Thernisien et al. 2011) consists of fitting a flux-rope model to simultaneous images of the *same* CME from the two STEREO spacecraft and sometimes from SOHO as well. The user varies a set of geometrical (e.g., height, angular width, tilt angle) and positional (longitude, latitude) parameters of the flux rope until an agreement is reached between the multi-viewpoint model projections and the corresponding images. Triangulation consists of identifying conjugate point(s) corresponding to the same feature in STEREO image pairs which retrieves the 3D positional information of the point(s). It can be applied to either 2D images or to time-elongation maps (j-maps) which correspond to stack-plots of 1D cuts along selected direction(s) in image time-series (e.g, Liu et al. 2010). Finally, single-viewpoint j-maps, under certain assumptions (e.g., fixed propagation angle, constant speed), can also supply 3D positional information of CMEs (Sheeley et al. 2009; Lugaz et al. 2010; Möstl et al. 2014).

The methods described above were applied to few dozen CMEs and supplied their kinematic profiles from the Sun to 1 AU (e.g., Colaninno et al. 2013; Möstl et al. 2014). These profiles were used to predict the time of arrival (ToA) and speed of these CMEs at 1 AU. This was achieved by extrapolation of the derived kinematics, assuming for example constant speed, from a given point in the heliosphere to 1 AU, which were then compared with the actual ToAs and speeds of the corresponding ICMEs when they reached 1 AU as determined by in-situ observations. The

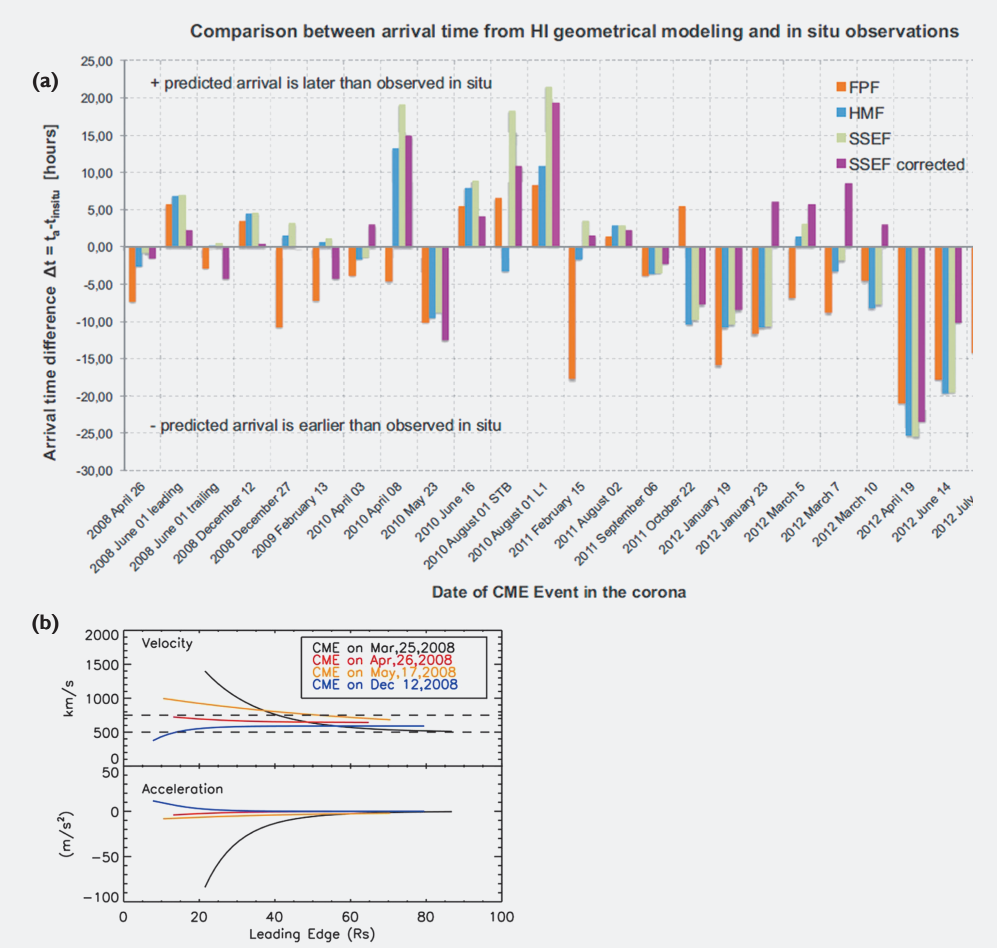


***Figure 4:*** Left panel. Comparison between CME arrival times at 1 AU for various events as inferred from various extrapolation schemes of their coronal/heliospheric kinematics deduced from STEREO observations with the corresponding in-situ arrival times. From Möstl et al. (2014). Right panel. Radial evolution of the speed (upper plot) and of the acceleration of several CMEs as deduced from STEREO observations. Differences between fast and slow CMEs close to Sun are progressively washed out suggesting the action of an aerodynamic drag force. From Poomvises et al. (2010).

predicted ToA were found within ±(6-8) hours from the observed ones (e.g. left panel of Figure 4). This is a significant improvement over previous determinations of ToA by single-viewpoint SOHO observations yielding agreement with observations within ±15 hours (Gopalswamy et al. 2001).

The following forces act on CMEs in the radial direction (e.g., Chen 1989): gravity, Lorentz and aerodynamic drag force. Owing to its rapid radial fall-off, gravity becomes insignificant relatively close to the Sun. Lorentz forces, arising from misaligned currents and magnetic fields within the flux rope and in the ambient medium, assume main role relatively close to the Sun, during the initiation and the early propagation phase of CMEs, although departures from force-freeness could exist in coronagraph fields of view, as well (Subramanian et al. 2014). Given the lack of *routine direct* observations of magnetic fields and currents in CMEs and the corona, we do not have a direct access to the corresponding Lorentz forces. The aerodynamic drag force (e.g., Vršnak 2001; Cargill 2004; Byrne et al. 2010; Vršnak et al. 2013; Mishra & Srivastava 2013; Hess & Zhang 2015; Patsourakos et al. 2015; Sachdeva et al. 2015; Zic et al. 2015) is associated with the relative motion between a CME and the solar wind and reflects momentum exchanges between them. This force depends on a number of CME (velocity, mass, area, density) and solar wind (velocity, density) parameters as well as on the drag-force coefficient. The latter is either parametrized (e.g., Byrne et al. 2010; Vršnak et al. 2013), calculated from theory of turbulent solar wind viscosity (Subramanian, Lara, & Borgazzi 2012) or directly from the analysis of related MHD simulations (Cargill 2004). Under the influence of the drag force, fast (slow) CMEs (with respect to the solar wind) tend to decelerate (accelerate) in order to catch up with the solar wind flow. These expectations, and particularly for fast CMEs, are supported by STEREO observations showing that the near-Sun differences in the speeds of slow and fast CMEs are washed out further away at distances of few tens of Rs (e.g., Poomvises, Zhang, & Olmedo 2010; right panel of Figure 4). For slow CMEs, with speeds close to that of the ambient solar wind, the action of a drag force is less certain (Sachdeva et al. 2015).

STEREO observations revealed and quantified various modulations that CMEs are experiencing during their propagation in the corona and the IP space. These include departures from radial propagation in terms of longitudinal and latitudinal deflections and rotations of the CME axis. Using a combination of solar observations of the source regions, geometrical modeling of the coronal observations, and fittings of the corresponding in-situ observations for a set of Earth-directed CMEs, Isavnin et al. (2014) found that the analyzed CMEs exhibited Sun-to-Earth longitudinal and latitudinal deflections in the range [–28°, 14°] and [20°, 49°], respectively, and rotations in the range [4°, 164°]. Most of these modulations (~ 60%) occurred relatively close to the Sun, within a distance of ~ 30 Rs. CME deflection could be explained in terms of their channeling towards regions of weak magnetic field (i.e., away from active regions and coronal holes) or by interaction with the Parker-spiral IP magnetic field for weak-field CMEs (e.g., Gopalswamy et al. 2001; Wang et al. 2004; Gui et al. 2011; Kay et al. 2013). CME rotations could arise for a number of reasons described in detail

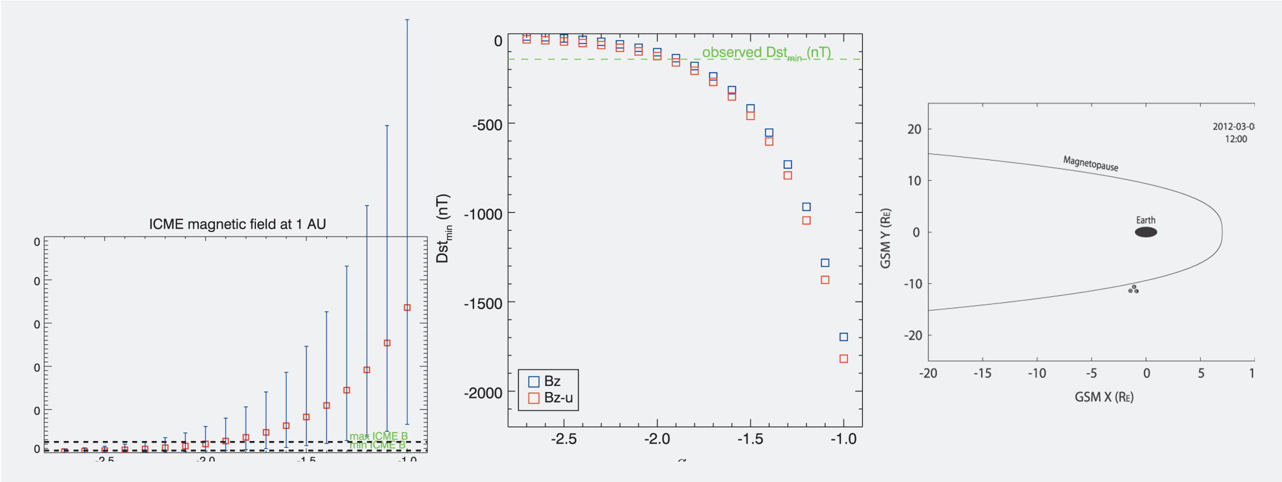


***Figure 5:*** Left panel. Extrapolated near-Sun (13 Rs) CME magnetic field to 1 AU (boxes) as a function of the exponent, $\alpha_B$, of a power-law describing its radial evolution from 13 Rs to 1 AU. The two horizontal lines correspond to the observed in-situ minimum/maximum magnetic field of the IC-ME at 1 AU. Middle panel. Predicted minimum Dst index (corresponding to the peak of the geomagnetic storm) as a function of $\alpha_B$. The horizontal dashed line corresponds to the observed minimum Dst. Right panel. Simulation of the magnetosphere after the arrival of the shock associated with the analyzed CME at 1 AU. The solid line corresponds to a projection of the magnetopause and the three dots correspond to the locations of three of the THEMIS spacecraft (Angelopoulos 2008), which prior to shock arrival, were inside the magnetosphere. From Patsourakos et al. (2016).

in, for example, Kliem et al. (2012), which include relaxation of twist of an erupting flux rope, reconnection of the CME with the ambient corona, and torque forces resulting from the Lorentz forces applied to the two legs of the CME flux rope. The above result from the axial electric current flowing along the flux rope and the external magnetic field.

Additional effects influencing CME propagation could arise from CME-CME interactions. This could occur, particularly during periods of high activity, when a faster CME catches up with a slower one, and can lead to the formation of composite and complex structures. Sometimes, CME-CME interactions can lead to an increase of the geoeffectiveness of the ejecta, by for example, enhancing their magnetic field (e.g., Lugaz et al. 2012; Shen et al. 2012; Temmer et al. 2012; Liu et al. 2014; Mishra et al. 2015).

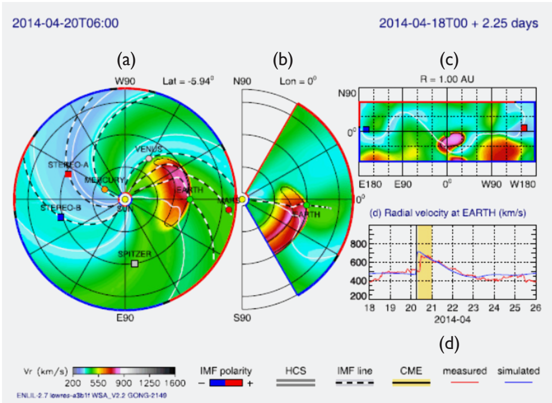


***Figure 6:*** Example of an MHD simulation of a CME evolution in the inner heliosphere (Mays et al. 2015b). Velocity contour plot for (a) constant latitude Earth-containing plane, (b) Earth-containing meridional plane, and (c) synoptic (longitude-latitude) map at 1 AU. Panel (d) contains time-series of the radial speed at 1 AU as derived from the simulation (blue) and from the actual in-situ observations (red).

## Coupling evolution from Sun to Earth

The recent availability of comprehensive instrumentation supplying observations of the Sun, its corona and the inner heliosphere (e.g., SOHO, Hinode, STEREO, SDO, Messenger, Venus Express), 1 AU (e.g., ACE, WIND) and the magnetosphere (e.g., CLUSTER, THEMIS) makes it possible to perform synergistic studies of solar transients all way from the Sun to 1 AU and geospace or to other inner solar system planets (e.g., Möstl et al. 2009; Roulliard et al. 2009; Lynch et al. 2010; Wood et al. 2011; Temmer et al. 2012; Liu et al. 2013; Nieves-Chinchilla et al. 2013; Möstl et al. 2014; Savani et al. 2015).

A recent study of this type is described in Patsourakos et al. (2016), where an ultra-fast (>2000 km s-1) CME launched from the Sun on 7 March 2012, was extensively studied from its initiation in the low-corona, to the outer corona, the IP medium and geospace. This event was associated with intense space weather phenomena, including one the largest geomagnetic storms and solar energetic particle events of solar cycle 24 (Kouloumvakos et al. 2016). The CME seed was a flux rope formed during confined flaring events several hours prior to the CME onset (Chintzoglou et al. 2016; Syntelis et al. 2016; e.g., left panel of Figure 3). This study applied a novel and robust method of inferring the near-Sun magnetic field of CMEs to the observed event. The basic inputs of the method (CME magnetic helicity, radius and length) can be easily deduced from photospheric vector magnetograms and coronal images. The near-Sun magnetic field of the observed CME was then extrapolated to 1 AU (left panel of Figure 5). It is important to develop robust methods of CME-ICME magnetic field calculation, since we currently lack routine direct diagnostics of this key parameter for their energetics, dynamics and geoeffectiveness (see also Chen & Kunkel 2010 and Savani et al. 2015 for other recent efforts in this area). The extrapolated CME magnetic field to 1 AU along with its speed, determined from a drag-based model, were used to predict the maximum of the corresponding geomagnetic storm by applying an empirical law (middle panel of Figure 5). The output of a data-constrained MHD modeling of the associated shock from 21 Rs to 1 AU was used as a boundary condition to a magnetospheric model (Tsyganenko

& Sitnov 2005; Tsironis et al. 2015) in order to predict the magnetospheric compression resulting from the arrival at 1 AU of the shock associated with the ICME (right panel of Figure 5). The magnetospheric compression was a key factor in the observed radiation-belt dynamics which included ultra-low-frequency wave enhancements and relativistic-electron dropouts.

Given the disparate temporal and spatial scales and physical regimes throughout the Sun-geospace domain, it is currently challenging to fully simulate with a single code CMEs from flux emergence, initiation, propagation and geomagnetic impact. Rather, the full domain is split into sub-domains (e.g., convection zone and inner corona, outer corona and IP medium, magnetosphere) where solutions are more tractable (e.g the various solar, coronal, IP and magnetospheric models hosted by NASA's Community Coordinated Modeling Center (CCMC[1]). Sometimes, the various sub-domains are been linked by supplying the output of one as boundary condition for another, as this is done in, for example, the frame of the Space Weather Modeling Framework[2]. Recent examples of CME propagation modeling, sometimes incorporating initiation as well, can be found in Lynch et al. (2004); Manchester et al. (2004); Jacobs et al. (2009); Lugaz et al. (2010); Lionello et al. (2013); Shen et al. (2014); Mays et al. (2015a); Wu et al. (2016).

Observationally-constrained MHD modeling of CME propagation can be, for example, performed by the ENLIL code (Odstrcil & Pizzo 2009) which launches CME-like hydrodynamic disturbances at its inner boundary at 21 Rs and propagates them through the heliosphere (e.g., Figure 6). The properties of the applied disturbances (e.g., CME initial speed, width, location) are constrained by the geometrical modeling of STEREO observations and give a ToA at 1 AU uncertainty of ~ 12 hours (Mays et al. 2015b). The CME is immersed into a background solar wind constructed using empirical solar wind models which use synoptic observations of the photospheric magnetic field. ENLIL, under operational mode at CCMC, can supply quasi-real time predictions of CMEs' ToAs.

1. http://ccmc.gsfc.nasa.gov/
2. http://csem.engin.umich.edu/tools/swmf/

## Conclusions and the way forward

Recent advances in our observational and modeling capabilities led to significant progress in our understanding of the origins of CMEs and their propagation and evolution in the corona and the IP space. These include the following:

- CMEs during their onsets, and further away in coronagraphic fields of view, are flux ropes.
- Pre-eruptive flux ropes could arise during confined flaring events.
- Our current predictive capability of CME arrival at 1 AU is of the order of few hours.
- CMEs experience significant deflections and rotations from Sun to 1 AU with most of these modulations taking relatively close to the Sun.
- Methods of inference of the near-Sun magnetic field of CMEs are emerging.

Important areas of improvement include the following:

- Obtain better *boundary conditions* for magnetic field extrapolations and solar wind models. For example, using chromospheric magnetic field data to extrapolate the magnetic field over CME-hosting regions, could be more appropriate than using photospheric data, since the chromosphere satisfies better the force-free condition on which magnetic field extrapolations are based. Moreover, global solar wind models used in both observational and theoretical studies of CME propagation and evolution rely on synoptic (full-sphere) maps of the photospheric magnetic field which need almost a month worth of data. This could potentially limit the scope of such calculations, particularly during periods of significant activity.
- Obtain better observational *constraints of the near-Sun properties* of the ambient solar wind and CMEs. CME propagation and evolution depends critically on the properties of the background solar wind, particularly close to the Sun. In addition, we have currently to rely upon indirect methods to infer the very crucial for many purposes CME magnetic field.

Upcoming Solar Orbiter (SolO[3]; Muller et al. 2014), Solar Probe Plus (SPP; Fox et al. 2015), and PROBA III (Renotte et al. 2014) missions currently scheduled for launch in 2018 and 2019 as well as the under study L5 mission concept, will help into addressing these issues. SolO will supply in-situ and remote sensing observations of the Sun and the heliosphere up to 33 degrees above the ecliptic plane reaching a perihelion of ~ 0.28 AU, while SPP will supply imaging and in-situ observations flying inside the solar corona reaching a perihelion of ~ 10 Rs. Synergies between these mission will, for example, supply in-situ observations of CME–ICME magnetic field speed and upstream conditions both at ~ 10 Rs and 0.3 AU when both spacecraft are aligned. PROBA III will supply conogragraphic observations of CME onsets very close to the limb. The STEREO CME ToA observations discussed in the previous Sections were carried out when the STEREO spacecraft were separated by ~ 60 degrees from the Sun-Earth line. This suggests that coronal/heliospheric observations from the L5 point of the Sun-Earth system, as envisaged in the frame of an L5 mission (e.g, Trichas et al. 2015; Vourlidas 2015), could supply an ideal platform for predicting the ToA of Earth-directed CMEs at 1 AU.

These observational capabilities along with ongoing developments in modeling (e.g., data-driven models of CME initiation and solar wind) and theory (e.g., modeling of solar wind turbulence) open new exciting avenues for further advances in our understanding of CMEs.

3. https://cloud.cosmos.esa.int/public.php?service=files&t=d30564c6698287ac6a7b18f9094392 1d

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## References


Amari, T., Luciani, J. F., Mikic, Z., & Linker, J. 2000, ApJL, 529, L49

Amari, T., Canou, A., & Aly, J. J. 2014, Nature, 514, 465

Angelopoulos, V. 2008, SSRV, 141, 5

Antiochos, S. K., DeVore, C. R., & Klimchuk, J. A. 1999, ApJ, 510, 485

Archontis, V. & Török, T. 2008, A&A, 492, L35

Archontis, V., Hood, A. W., & Tsinganos, K. 2013, ApJ, 778, 42

Aulanier, G., Török, T., Démoulin, P., DeLuca, E. E. 2010, ApJ, 708, 314

Burlaga, L., Sittler, E., Mariani, F., & Schwenn, R. 1981, JGR, 86, 6673

Byrne, J. P., Maloney, S. A., McAteer, et al. 2010, Nature Communications, 1, 74

Cargill, P. J. 2004, Solar Physics, 221, 135

Chen, J. 1989, ApJ, 338, 453

Cheng, X., Zhang, J., Liu, Y., & Ding, M. D. 2011, ApJL, 732, L25

Cheng, X., Ding, M. D., Zhang, J., et al. 2014, ApJ, 789, 93

Chintzoglou, G., Patsourakos, S., & Vourlidas, A. 2015, ApJ, 809, 34

Colaninno, R. C., Vourlidas, A., & Wu, C. C. 2013, Journal of Geophysical Research (Space Physics), 118, 6866

Georgoulis, M. K., & Rust, D. M. 2007, ApJL, 661, L109

Fan, Y. 2009, ApJ, 697, 1529

Fang, F., Manchester, W., IV, Abbett, W. P., & van der Holst, B. 2012, ApJ, 754, 15

Fox, N. J., Velli, M. C., Bale, S. D., et al. 2015, SSRV, Online First

Gopalswamy, N., A. Lara, S. Yashiro, et al. 2001, Journal of Geophysical Research (Space Physics), 106, 29207

Gopalswamy, N., Yashiro, S., Michalek, G., et al. 2009a, Earth Moon and Planets, 104, 295

Gopalswamy, N., Mäkelä, P., Xie, H. et al. 2009b, Journal of Geophysical Research (Space Physics), 114, A00A22

Green, L. M., Kliem, B., & Wallace, A. J. 2011, A&A, 526, A2

Guo, Y., Ding, M. D., Cheng, X., et al. 2013, ApJ, 779, 157

Gui, B., Shen, C., Wang, Y., et al. 2011, Solar Physics, 271, 111

Hess, P., & Zhang, J. 2015, ApJ, 812, 144

Howard, R. A., Moses, J. D., Vourlidas, A., et al. 2008, Space Science Reviews, 136, 67

Isavnin, A., Vourlidas, A., & Kilpua, E. K. J. 2014, Solar Physics, 289, 2141

Jensen, E. A., Hick, P. P., Bisi, M. M., et al. 2010, Solar Physics, 265, 31

Jian, L., Russell, C. T., Luhmann, J. G., & Skoug, R. M. 2006, Solar Physics, 239, 393

Kay, C., Opher, M., & Evans, R. M. 2013, ApJ, 775, 5

Kliem, B. & Török, T. 2006, Physical Review Letters, 96, 255002

Kliem, B., Török, T., & Thompson, W. T. 2012, Solar Physics, 281, 137

Kouloumvakos, A., Patsourakos, S., Nindos, A., et al. 2016, ApJ, 821, 31

Kunkel, V., & Chen, J. 2010, ApJL, 715, L80

LaBonte, B. J., Georgoulis, M. K., & Rust, D. M. 2007, ApJ, 671, 955

Leake, J. E., Linton, M. G., Török, T. 2013, ApJ, 778, L99

Leake, J. E., Linton, M. G., & Antiochos, S. K. 2014, ApJ, 787, 46

Lemen, J. R., Title, A. M., Akin, D. J. et al. 2012, Solar Physics, 275, 17

Liu, Y., Davies, J. A., Luhmann, J. G., et al. 2010, ApJL, 710, L82

Liu, Y. D., Luhmann, J. G., Lugaz, N., et al. 2013, ApJ, 769, 45

Liu, Y. D., Luhmann, J. G., Kajdič, P. et al. 2014, Nature Communications, 5, 348

Lugaz, N., Hernandez-Charpak, J. N., Roussev, I. I., et al. 2010, ApJ, 715, 493

Lugaz, N., Farrugia, C. J., Davies, J. A., et al. 2012, ApJ, 759, 68

Lynch, B. J., Antiochos, S. K., MacNeice, P. J., et al. 2004, ApJ, 617, 589

Lynch, B. J., Antiochos, S. K., DeVore et al. 2008, ApJ, 683, 1192

Lynch, B. J., Li, Y., Thernisien, A. F. R., et al. 2010, Journal of Geophysical Research (Space Physics), 115, A07106

Manchester, W. B., Gombosi, T. I., Roussev, I., et al. 2004, Journal of Geophysical Research (Space Physics), 109, A01102

Mays, M. L., Thompson, B. J., Jian, L. K., et al. 2015b, ApJ, 812, 145

Mays, M. L., Taktakishvili, A., Pulkkinen, A., et al 2015b, Solar Physics, 290, 1775

Mishra, W., & Srivastava, N. 2013, ApJ, 772, 70

Mishra, W., Srivastava, N., & Singh, T. 2015, Journal of Geophysical Research (Space Physics), 120, 10

Möstl, C., Farrugia, C. J., Temmer, M., et al. 2009, ApJL, 705, L180

Möstl, C., Amla, K., Hall, J. R., et al. 2014, ApJ, 787, 119

Mueller, D., St Cyr, O. C., Zouganelis, Y., & Gilbert, H. R. 2014, 40th COSPAR Scientific Assembly, 40

Lionello, R., Downs, C., Linker, J. A., et al. 2013, ApJ, 777, 76

Nieves-Chinchilla, T., Vourlidas, A., Stenborg, G., et al. 2013, ApJ, 779, 55

Nindos, A., & Andrews, M. D. 2004, ApJL, 616, L175

Nindos, A., Patsourakos, S., Vourlidas, A., & Tagikas, C. 2015, ApJ, 808, 117

Odstrcil, D., & Pizzo, V. J. 2009, Solar Physics, 259, 297

Ontiveros, V., & Vourlidas, A. 2009, ApJ, 693, 267

Patsourakos, S., Vourlidas, A., & Stenborg, G. 2013, ApJ, 764, 125

Patsourakos, S., Georgoulis, M. K., Vourlidas, A., et al. 2016, ApJ, 817, 14

Poomvises, W., Zhang, J., & Olmedo, O. 2010, ApJL, 717, L159

Riley, P., Lionello, R., Mikić, Z., & Linker, J. 2008, ApJ, 672, 1221-1227

Renotte, E., Baston, E. C., Bemporad, A., et al. 2014, Proceedings of the SPIE, 9143, 91432M

Rouillard, A. P., Davies, J. A., Forsyth, R. J., et al. 2009, Journal of Geophysical Research (Space Physics), 114, A07106

Sachdeva, N., Subramanian, P., Colaninno, R., & Vourlidas, A. 2015, ApJ, 809, 158

Savani, N. P., Vourlidas, A., Szabo, A., et al. 2015, Space Weather, 13, 374

Savcheva, A., Pariat, E., van Ballegooijen, A., et al. 2012, ApJ, 750, 15

Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, Solar Physics, 275, 207

Schrijver, C. J. 2007, ApJL, 655, L117

Sheeley, N. R., Walters, J. H., Wang, Y. M., & Howard, R. A. 1999, JGR, 104, 24739

Shen, C., Wang, Y., Wang, S., et al. 2012, Nature Physics, 8, 923

Shen, F., Shen, C., Zhang, J., et al. 2014, Journal of Geophysical Research (Space Physics), 119, 7128

Song, H. Q., Zhang, J., Chen, Y., & Cheng, X. 2014, ApJL, 792, L40

Subramanian, P., Lara, A., & Borgazzi, A. 2012, Geophysical Research Letters, 39, L19107

Subramanian, P., Arunbabu, K. P., Vourlidas, A., & Mauriya, A. 2014, ApJ, 790, 125

Sun, X., Hoeksema, J. T., Liu, Y., et al. 2012, ApJ, 748, 77

Syntelis, P., Archontis, V., Gontikakis, C., & Tsinganos, K. 2015, A&A, 584, A10

Syntelis, P., Gontikakis, C., Patsourakos, S., & Tsinganos, K. 2016, A&A, 588, A16

Temmer, M., Vršnak, B., Rollett, T., et al. 2012, ApJ, 749, 57

Thernisien, A., Vourlidas, A., & Howard, R. A. 2009, Solar Physics, 256, 111

Trichas, M., Gibbs, M., Harrison, R., et al. 2015, Hipparchos, Vol 2, Issue 12, 25

Tsironis, C., Anastasiadis, A., Katsavrias, C., & Daglis, I. A. 2016, Annales Geophysicae, 34, 171

Tsyganenko, N. A., & Sitnov, M. I. 2005, JGRA, 110, 3208

Tziotziou, K., Georgoulis, M. K., & Raouafi, N. E. 2012, ApJL, 759, L4

Tziotziou, K., Georgoulis, M. K., & Liu, Y. 2013, ApJ, 772, 115

van Ballegooijen, A. A., & Martens, P. C. H. 1989, ApJ, 343, 971

Vourlidas, A., Howard, R. A., Esfandiari, E., et al. 2010, ApJ, 722, 1522-1538

Vourlidas, A., Colaninno, R., Nieves-Chinchilla, T., & Stenborg, G. 2011, ApJL, 733, L23

Vourlidas, A., Lynch, B. J., Howard, R. A., & Li, Y. 2013, Solar Physics, 284, 179

Vourlidas, A. 2015, Space Weather, 13, 197

Vršnak, B. 2001 Solar Physics, 202, 17

Vršnak B., Žic, T., Vrbanec, D., et al. 2013, Solar Physics, 285, 295

Wang, Y., Shen, C., Wang, S., & Ye, P. 2004, Solar Physics, 222, 329

Wiegelmann, T. 2004, Solar Physics, 219, 8

Wood, B. E., Wu, C. C., Howard, R. A., et al. 2011, ApJ, 729, 70

Wu, C. C., & Lepping, R. P. 2005, Journal of Atmospheric and Solar-Terrestrial Physics, 67, 283

Wu, C. C., Liou, K., Vourlidas, A., et al. 2016, Journal of Geophysical Research (Space Physics), 121, 1839

Zhang, J., Cheng, X., & Ding, M. D. 2012, Nature Communications, 3, 747

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# The 12th Hellenic Astronomical Conference

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 well over 100 scientists with research interests in Astronomy, Astrophysics, and Space Physics.

The 12th Conference of Hel.A.S. took place in Thessaloniki, from June 28 to July 2, 2015 and attracted more than 160 participants.

## Invited Plenary Speakers

- Prof. S. Capozziello (University of Napoli, Italy)
- Dr. D. Elbaz (CEA Saclay, France)
- Dr. P. Kalas (University of Berkeley, USA)
- Dr. A. Morbidelli (Observatory of Nice, France)
- Prof. M. McCaughrean (European Space Agency)

## Invited Session Speakers

- **Session 1:** C. Efthymiopoulos (Academy of Athens, Greece), P. Gallagher (Trinity College Dublin, Ireland), T. Sarris (Democritus University of Thrace, Greece)
- **Session 2:** A. Georgakakis (National Observatory of Athens, Greece and MPE, Germany), G. Magdis (University of Oxford, UK), I. Papadakis (University of Crete, Greece), V. Pavlidou (University of Crete, Greece)
- **Session 3:** T. Apostolatos (University of Athens, Greece), S. Basilakos (Academy of Athens, Greece), K. Glampedakis (University of Murcia, Spain)
- **Session 4:** A. Udalski (University of Warsaw, Poland), A. Zezas (University of Crete, Greece)

**Special Session:** A Special Session discussing the Greek-ESA relations and aiming to strengthen the ties between the Greek scientific and technological communities took place on Monday, June 29, 2015.

**Public Outreach Talk:** The customary Public Outreach Talk of the Conference took place at the Conference Room of the City Hall of Thessaloniki on Sunday, June 28, 2015. Dr. Stamatios Krimigis (The Johns Hopkins University Applied Physics Laboratory, USA and Academy of Athens, Greece) delivered the the talk, entitled "Το πρώτο ανθρώπινο ταξίδι στον Γαλαξία: Η Οδύσσεια των διαστημοπλοίων Voyager 1 και 2".

# International Meetings and Summer Schools in Greece in 2016

Year 2016 has proved to be a prolific year, marked by intense conference and summer school activity in Greece. Between late April and early October, a total of ten (10) international gatherings (approximately two per month) have, are or will be taking place in various attractive parts of the country, namely Crete, Mykonos, and Katerini, besides Athens. The following table summarizes these meetings in order of meeting dates and provides web links for additional information, while brief presentations for most of them follow. These presentations have been composed by the various meeting organizers, showcasing the remarkable potential of the Greek astronomy and astrophysics community that Hel.A.S. proudly represents.

| Dates (2016) | Place | Short Name | Full Name | Meeting webpage |
|---|---|---|---|---|
| 26-29 April | Kolymbari, Crete | | Escape of Lyman Radiation from Galactic Labyrinths | www.iastro.pt/research/conferences/lyman2016/ |
| 22-24 May | Chania, Crete | ADA8 | Astronomical Data Analysis 2016 Summer School | ada8.cosmostat.org |
| 24-27 May | Chania, Crete | COSMO21 | Statistical Challenges in 21$^{st}$ Century Cosmology | cosmo21.cosmostat.org |
| 6-11 June | Chania, Crete | SNR2016 | Supernova Remnants: An Odyssey in Space After Stellar Death | snr2016.astro.noa.gr |
| 15-18 June | Mykonos | | Hot Spots in the XMM Sky | www.astro.auth.gr/~xmmcosmo16/ |
| 19 June - 2 July | Heraklion, Crete | NEON School | Network of European Observatories in the North 2016 Observing School | www.iap.fr/neon/neon_schools/2016/ |
| 4-8 July | Athens | EWASS 2016 | European Week of Astronomy and Space Science | eas.unige.ch/EWASS2016/ |
| 11-15 July | Athens | | 2$^{nd}$ Hel.A.S. Summer School | www.helas.gr/school/2016/ |
| 19-22 September | Mykonos | NEB-17 | Recent Developments in Gravity | www.hsrgc.gr/neb17/ |
| 3-7 October | Paralia Katerini | | The ISM-SPP Olympian School of Astrophysics 2016 | school2016.olympiancfa.org |

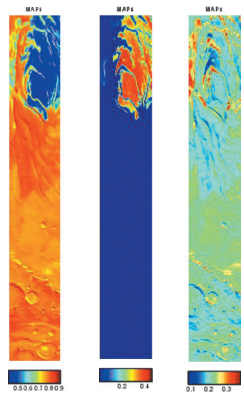
# ADA8-Astronomical Data Analysis 2016 Summer School

***May 22-24, Chania, Crete***

Held regularly since 2001, the ADA –Astronomical Data Analysis– conference series has been focused on algorithms for information extraction from astrophysics data sets. It became a strongly interdisciplinary forum where researchers from diverse fields such as Astronomy, Statistics, Mathematics and Computing could interact. This conference series has been characterized by a range of innovative themes, including multi-scale geometric transforms such as the curvelet transform, compressed sensing and clustering, always remaining closely linked to front-line open problems and issues in Astronomy.

Along many of its editions, the ADA conference series included hands-on tutorial sessions on various topics of advanced data processing. In the era of large astronomical surveys that are grappling with unsolved methodological and data challenges, transforming Data into Science is a huge, and exciting, problem, and a large fraction of modern Astronomy depends on this. Nevertheless, postgraduate courses can hardly cope with the pace of development of the modern data analysis methods and tools that may enable researchers to make the best use of their data. This was the main focus of the **ADA8 2016 Summer School held in Chania last May**: ***to present advanced data analysis methods and algorithms and to demonstrate how to use publicly available codes to improve knowledge extraction from astronomical datasets, enabling a better Science.***

The tutorials presented in the Summer School were not intended exclusively for an audience with background in Astronomy, and were mainly aimed for young researchers at MSc, PhD and postdoc levels, albeit other researchers have also attended the School. This year ADA took place on the days preceding the COSMO21 conference, both events took place at the same venue and the inscription in COSMO21 included the possibility to participate in the ADA8 Summer School.



(a) (b) (c)

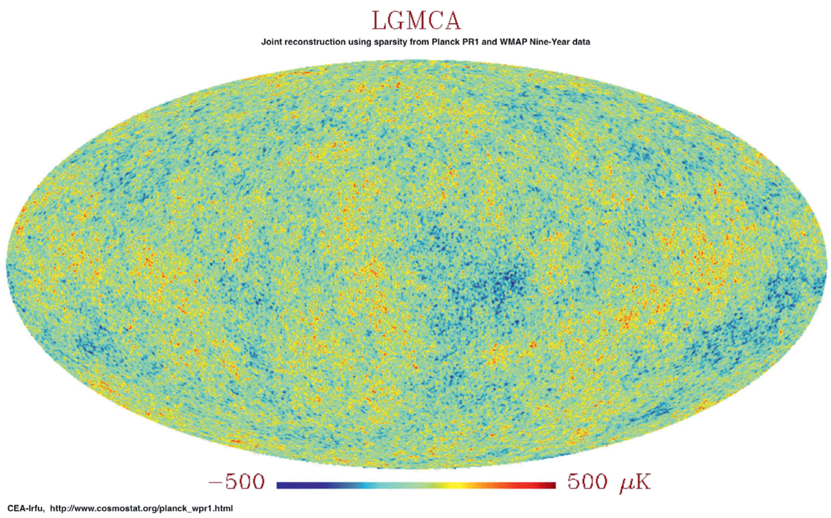
Abundance maps of (a) dust, (b) $CO_2$ and (c) $HO_2$ at the South Cup of Mars obtained by applying a Bayesian unmixing algorithm (MAPs) on hyperspectral OMEGA/Mars Express data.

# Statistical Challenges in 21st Century Cosmology (COSMO21)

***May 24-27, Chania, Crete***

Over the past 20 years the increasing complexity and larger volume of astronomical data has triggered a closer interaction between astronomers and statisticians, creating a new scientific discipline that is now widely called Astrostatistics. The new sophisticated tools for comparing theoretical predictions with observations in astronomy are statistical in nature and novel mathematical techniques in classifying or compressing data, such as sparsity and compressed sensing, have been developed.

The COSMO21 meeting has been especially timely from the point of view of all sky cosmological surveys, where application of a fully Bayesian analysis is extremely demanding computationally. Moreover, large surveys such as




The cleanest CMB map ever produced based on WMAP and Planck data, using the Local-Generalized Morphological Component Analysis (L-GMCA) method (Bobin et al. A&A, 2016, in press).

Pan-STARRS will cover 3π steradians of the sky producing data of petabyte size while the Dark Energy Survey and the VST KiDS surveys will be well underway presenting similar difficulties in the data analysis. Furthermore, the cosmological community is preparing for LSST and Euclid, a survey of a large fraction of the sky at an angular resolution close to that of the Hubble Space Telescope. Wide-field spectroscopic cosmology surveys of will also be targeting over 10 million objects with a spectral resolution of 5000, while the SKA precursors will be grappling with data challenges which currently are remain unsolved. These examples also highlight the big role, both now and even more in future, archival data analysis will be playing in astrophysics research.

The emphasis of the conference was on advances and methodological challenges in cosmology, and new results derived from advanced data analysis and modeling methods. The topics covered included studies of the cosmic microwave background (CMB), weak lensing, large-scale structure, high-z supernovae, tomography of the 21-cm radiation, multivariate classification and clustering, sparsity, wavelets, compressive sampling, machine learning, neural networks, supervised learning.

Over 120 participants from across the globe attended the conference, which included review talks by five world-renowned scientists as keynote speakers and five additional experts in cosmology. More information is available at:

http://cosmo21.cosmostat.org

Jean-Luc Starck,
CEA, France

Alan Heavens,
Imperial College London, UK

# Supernova Remnants: An Odyssey in Space after Stellar Death

***6-11 June, Chania, Crete***

The meeting "Supernova Remnants: An Odyssey in Space after Stellar death" will explore the exciting recent observational and theoretical progress in the structure, evolution and physics of SNRs. The Institute for Astronomy, Astrophysics, Space Applications & Remote Sensing of the National Observatory of Athens, will host ~150 participants on the island of Crete.


The conference will build upon spectral and imaging observations from radio to gamma-ray wavelengths of SNR blast waves, pulsar wind nebulae and SN ejecta and their interpretation through models and numerical simulations. The goals of the meeting are understanding the evolution of SNRs and their interaction with interstellar gas, elucidating the physical processes that govern shock waves and relativistic plasmas, and inferring characteristics of supernova explosions from SNR observations.

We will focus on narrowing the gap between observations and theories with the help of powerful new instrumentation such as hard X-ray and gamma-ray satellites, large optical telescopes, and sub-mm and low-frequency radio arrays on the one hand, and increasingly detailed and realistic numerical simulations on the other. New understanding of the nature of supernova remnants and processes that occur there offers new insights into the role of SNRs in the structure and evolution of galaxies and the nature of supernova explosions.

Information about the scientific topics, invited speakers, SOC, and LOC can be found on the conference website:

http://snr2016.astro.noa.gr

Panos Boumis & Alceste Bonanos
LOC co-chairs

# Hot spots in the XMM sky: Cosmology from X-ray to Radio

***15-18 June, Mykonos Island***

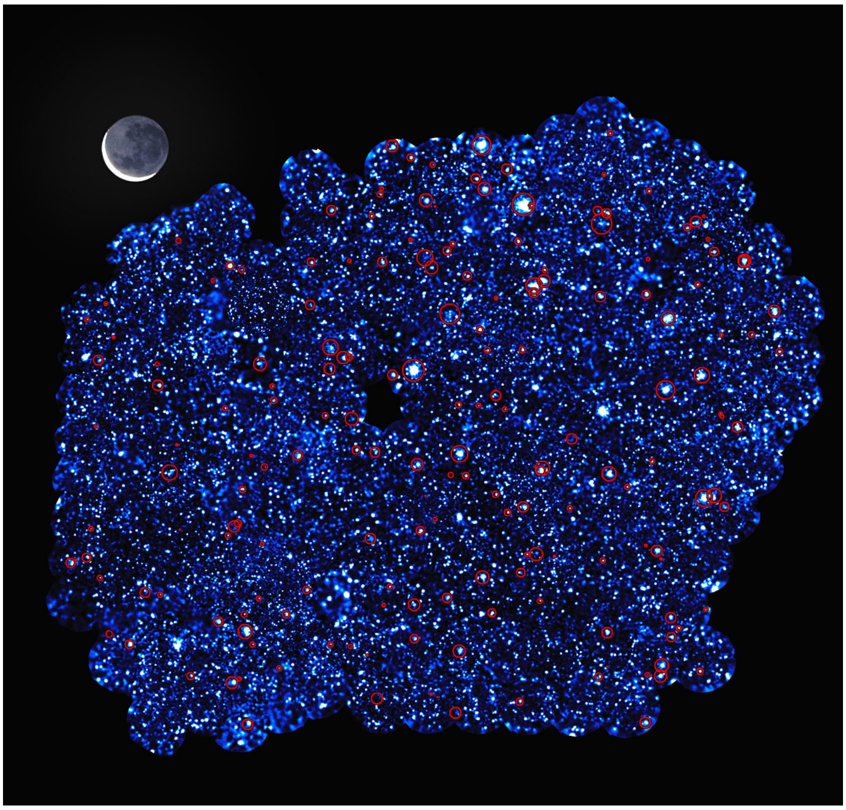
Hot and energetic extragalactic sources, namely clusters of galaxies and active galactic nuclei (AGN), play a key role in our understanding of the Cosmic Web and of structure formation, reveling also many aspects of gravitational physics. X-ray observations provide a highly effective means of detecting such sources and since the launch of the Chandra (NASA) and XMM-Newton (ESA) space observatories in 1999, our knowledge of clusters and AGN, out to cosmological distances, has transformed drastically. This period has also witnessed great advances in the scale and complexity of numerical simulations of galaxy clusters and supermassive black holes - from the details of individual systems to their cosmological context. The high-energy astrophysics and observational cosmology community is currently facing the challenge of using large surveys of galaxy clusters and AGN as precision cosmological probes, attempting to constrain the dark energy equation of state.

Considering the probable extension of the XMM mission for another twelve years, the meeting aims at (1) a review of the state-of-the art studies of the cosmic web, as revealed in X-rays in partnership with observations across the entire electromagnetic spectrum; (2) providing a framework to discuss holistic pictures of structure formation with the aid of numerical simulations; (3) exploring the scientific potential and feasibility of future extra-large, community-based surveys with XMM.

One of the meeting highlights will be the presentation of recent results from the XXL survey, the largest XMM program undertaken to date (6 Msec $2\times25$ sq. deg. – with some 500 clusters of galaxies and 25,000 AGN). The scientific committee of the collaboration that leads this program involves scientists from France, England, Belgium, Switzerland, Greece, Italy, Sweden, USA and Canada. The overall P.I. of the project is Dr. Marguerite Pierre of CEA, Saclay, while the P.I. for one of its two science themes, related to AGN, is Prof. Manolis Plionis, of the Aristotle University of Thessaloniki. Just recently, in December 2015, ESA announced the first results in an official communication. These first results were published in a special issue of the prestigious scientific journal Astronomy & Astrophysics:

http://www.aanda.org/2015-press-releases/1171

The following illustration shows the X-ray emission in one of the two areas of the sky (the moon is illustrated for size comparison) surveyed by XMM as part of this project, with marked the clusters of galaxies. The large number of bright (white) sources are AGN.



# Network of European Observatories in the North (NEON school)

***19 June - 2 July, Heraklion, Crete***

The **N**etwork of **E**uropean **O**bservatoires in the **N**orth organizes a yearly observational Summer School devoted to Observational Astronomy. The 2016 event will take place at the Skinakas Observatory and the University of Crete from June 19th to July 2nd, 2016.

The purpose of the summer schools is to provide the opportunity for young researchers to gain practical experience in observational techniques, data reduction and analysis. The NEON schools, which exist since year 1999, bring small groups of students directly to the telescope to do small research programs under the supervision of experienced astronomers. This goes the full way from the preparation of the observations to the data reduction and analysis, to end-up with the presentation of the scientific results. During two weeks, the participants have the chance to have hands-on real-life experience on the full cycle from proposal preparation to data reduction. The observing activities at the telescope in Skinakas will largely concentrate on the skills required to execute an observing program (imaging and spectroscopy). These practical exercises will be complemented by lectures on general observational techniques. These lecturers cover subjects such as telescope optics and imaging, spectroscopy, photometry, and detectors.

In addition, the participants have the opportunity to attend lectures on hot-topics of the present day astrophysics given by experts on the field. All the lectures will be given in the Physics Department building of the University of Crete.

The school is open to PhD students or early PostDocs in Astrophysics, who need to gain observing experience.

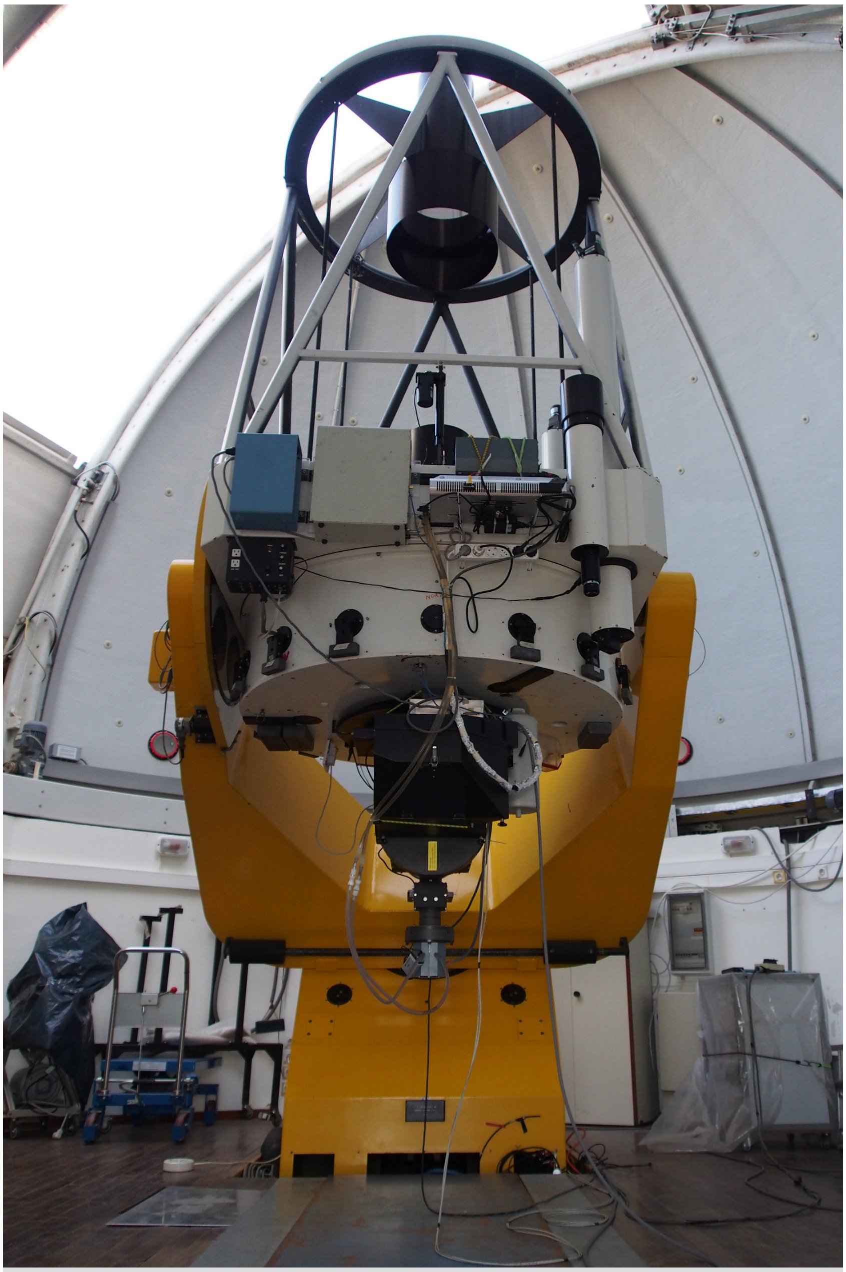
Previous editions of the NEON school have been organised in Calar Alto Observatory (Spain), Haute-Provence Observatory (France), Asiago Observatory (Italy), Roque de los Muchachos Observatory Spain), and Rozhen Observatory (Bulgaria).

The coordinator of the 2016 NEON School is Michel Dennefeld (IAP, Paris), while the following tutors have confirmed their presence: Pablo Reig, Lorenzo Morelli, Jairo Mendez, Nancy Elias-Rosa, Tapio Pursimo. The local coordinator is Iossif Papadakis (University of Crete). Confirmed experts that will give lectures are: R. Hook, S. Ortolani, V. Pavlidou, A. Zezas, H. Korhonen, K. Tsiganis, N. Kylafis, and G. Gilmore.

NEON Observing Schools are supported by OPTICON. For further information about the school, please visit the NEON School website:

http://skinakas.physics.uoc.gr/en/outreach/neon2016.html

**Pablo Reig**, **Chair of the LOC**



The 1.3-m telescope of the Skinakas Observatory where the observing activities of the NEON 2016 school will take place.

# European Week of Astronomy and Space Science 2016

***4-8 July, Athens***

The **European Week of Astronomy and Space Science** (EWASS) is the annual conference of the European Astronomical Society (EAS). This conference series started in 1992, under the name **Joint European and National Astronomical Meeting** (JENAM), with the EAS organizing its meeting every year at a different European country together with the corresponding National Astronomical Society. It was nearly 20 years ago, in 1997, when JENAM was held for the first time in Greece, near Thessaloniki, and it was organized together with the Hellenic Astronomical Society (Hel.A.S.), when our Society was just 4 years old. Since 2009, the EAS is organizing its annual conference (EWASS) independently at various places across Europe, with the number of participants increasing from a few hundred to more than a thousand. Thus, EWASS has become the major astronomical conference in Europe.


This year EWASS will be held in Athens, from the 4$^{th}$ to the 8$^{th}$ of July 2016. The conference venue is the Eugenides Foundation and the adjacent Metropolitan Hotel. Approximately 1000 participants are expected, not only from Europe but also from North and South America, Asia, Africa, and Australia. EWASS 2016 will have a rich scientific program with 17 Symposia and 12 Special Sessions. There will be 10 parallel sessions every day. Thus, nearly all subjects of Astrophysics will be covered, from Solar and Space Physics to Cosmology. Major talks will be given by 7 Plenary Speakers and also by the 5 recipients of the annual T. Brahe, L. Woltjer and MERAC prizes awarded by the EAS. One of the three MERAC prizewinners for the best doctoral thesis is Dr. Maria Petropoulou, a member of the Hel.A.S. In addition, there will be a Memorial and a Plenary Talk dedicated to Prof. Francesco Palla, a member of the EAS Council, who passed away unexpectedly earlier this year.

More information on EWASS 2016 can be found at:

http://eas.unige.ch/EWASS2016

Nikos Kylafis, *Co-chair of the SOC*

Vassilis Charmandaris, *Chair of the LOC*

# The 2$^{nd}$ Summer School of the Hellenic Astronomical Society

***11-15 July, Athens***

The Hellenic Astronomical Society (Hel.A.S.), in collaboration with the National Observatory of Athens (NOA) and the National and Kapodistrian University of Athens (UoA), under the initiative to offer knowledge and scientific training to the younger members, graduate students and young postdoctoral researchers of the Society, is organizing the 2$^{nd}$ Summer School titled: "Nuclear activity in galaxies" in Athens, from the 11$^{th}$ until the 15$^{th}$ of July 2016.

## Organizing Committees

*Scientific Organizing Committee (SOC):*

– N. Vlahakis (UoA – Chair),
– V. Charmandaris (NOA-UoC)
– I. Georgantopoulos (NOA)
– A. Mastichiadis (UoA)
– I. Papadakis (UoC)
– M. Xilouris (NOA)

*Local Organizing Committee (LOC):*

– N. Vlahakis (UoA – Chair)
– M. Xilouris (NOA)
– S. Boula (UoA)
– D. Kantzas (UoA)
– C. Sinis (UoA)
– E. Zoulekou (UoA)

## Summer School Registration

The School participation is limited to 30-35 persons. A registration fee of 60€ has been set to cover writing material and the coffee break costs. The registration fee will be paid in cash upon arrival. There will be a possibility to financially support a limited number of participants who will present their work during the last day of the school. In order to qualify you will also be asked (during the school) to provide your CV.

To register, please complete the registration file available at

http://www.helas.gr/school/2016/Reg_Form.docx

and send it by e-mail to

N. Vlahakis (vlahakis@phys.uoa.gr)
and to E. Xilouris (treasurer@helas.gr)

with a Subject: "Registration of 2nd Summer School of Hel.A.S."

before **June 11, 2016**.

## Summer School Venue

The 2nd Summer School of Hel.A.S. will take place at the Department of Physics of the University of Athens, situated in the Zografos University Campus. The School is sponsored by the National Observatory of Athens and the National and Kapodistrian University of Athens.

# The ISM-SPP Olympian School of Astrophysics 2016

***3-7 October, Paralia Katerini***

State-of-the-art Galactic/extragalactic observations, theoretical studies and advanced numerical models have provided great insights into the physics and chemistry of the interstellar medium (ISM). Several groups worldwide are investigating its life cycle and its significance in the overall star formation process from the low- to high-redshift Universe. This, however, has led to a plethora of interesting but thus far unanswered questions. In an attempt to provide an up-to-date overview of the ISM processes, the Olympian Centre for Astrophysics (OCfA, http://olympiancfa.org/), in collaboration with the Max Planck Institute at Garching (Munich, Germany) and a generous sponsorship by the ISM-SPP Priority Program 1573 of the German Foundation of Research (Deutsche Forschungsgemeinschaft), organizes "The ISM-SPP Olympian School of Astrophysics 2016" the week of 3-7 October 2016 in Paralia Katerini. OCfA is a non-profit organization founded in January 2015, aiming to promote actions related to Astrophysics and Space Physics in the prefecture of Pieria and facilitate the contact of young Greek graduate and postgraduate students with respective European and International astrophysical research.

Far-UV radiation, emitted by the two bright stars in this image, illuminates Polycyclic Aromatic Hydrocarbons (PAHs) that exist in the interstellar medium. PAHs are organic two-dimensional molecules consisting of carbon and hydrogen only that play a key role in ISMheating via the photoelectric effect. They are observed even in the Early Universe and are thought to be important components for the formation of the abiotic life. The image has been taken by the Spitzer Space Telescope (GLIMPSE360 survey). Credit: NASA/JPL-Caltech/2MASS/SSI/University of Wisconsin.

The School concerns graduate students, young PhD students and early career scientists and addresses the physics and dynamics of the Galactic and extragalactic ISM, astrochemistry of photoionization, photodissociation and molecular regions, hydrodynamical instabilities, turbulence (including magnetic fields), star formation processes from low-mass to high-mass stars, triggered versus non-triggered star formation, hydrodynamical simulations and comparison with observations. These topics will be covered with a series of review talks, academic lectures and hands-on day to work on basic hydrodynamical simulations and observational data by six distinguished scientists of the field: Robi Banerjee (University of Hamburg, Germany), Andreas Burkert (Ludwig-Maximilians Universitaet Muenchen, Germany), Kalliopi Dasyra (National and Kapodistrian University of Athens, Greece), Simon Glover (University of Heidelberg, Germany), Peter Schilke (University of Cologne, Germany), and Konstantinos Tassis (University of Crete, Greece). Participants will have an opportunity to present their own work during dedicated poster sessions, while following the successful tradition of previous OCfA international events, the opening ceremony will take place on Sunday October 2, 2016 with a public outreach lecture given by Dionisios Simopoulos, Director Emeritus of the Eugenides Planetarium.

In line with its scope, OCfA will try to financially support Greek-affiliated scientists (graduate & PhD students and young postdocs) to attend the school. They should contact OCfA:

ocfa@olympiancfa.org

for further information on how to receive such a support.

For further information about the school, including venue location, registration, financial support and abstract submission deadlines, please visit the ISM-SPP Olympian School of Astrophysics 2016 website:

http://school2016.olympiancfa.org/

# Back issues of Hipparchos

Hipparchos is the official newsletter of the Hellenic Astronomical Society. It is distributed by post to the members of the society. You can download back issues from: **http://www.helas.gr/news.php**