European Commission

Research and Innovation action

NEW DISCOVERIES FROM GAMMA-RAY POLARIZATION OF COSMIC ACCELERATORS

(POLCA)

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List of participants

Participant No.	Participant organisation name	Country
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1. Excellence

1.1 Objectives

We propose to re-analyze all data of suitably bright cosmic sources measured with the instruments IBIS (*I*mager on *B*oard the *I*ntegral *S*atellite) and SPI (*SP*ectrometer on *I*ntegral) of ESA's INTEGRAL satellite with newly developed analysis tools in order to investigate the gamma-ray polarization properties of these sources. Through this work we aim at obtaining new scientific insight into the physical processes of astrophysical sources, and thus build a framework which optimizes the science potential of future missions.

Our science goals are built on four pillars:

Our new method has the potential to better constrain polarization parameters due to the inclusion of other information (e.g. the spectrum) **See § 1(C2)**	The success of our time-resolved analysis approach calls for re-analysis of old data, since the previous approach of co-adding all data could have smeared out the signal **See § 1(B3)**	Extend our approach of time-resolved polarization to energy-resolved polarization measurements **See § 1(D3)**	INTEGRAL IBIS & SPI are the best-suited instruments with a large database to perform systematic new polarization analysis **See § 1(C3)**

Our science goals/questions can be reached by re-analysing all INTEGRAL data of the brightest sources of various source types, and can be summarized as follows:

1) Is a changing polarization angle throughout the burst activity a general feature in GRB prompt emission? (So far it is measured only in one GRB.)
2) Will we find consistent polarization results for the Crab between different instruments? (Previous IBIS and SPI results are contradictory.)
3) Is the jet-emission of microquasars polarized? V404 Cyg had a super-bright high-energy outburst in 2015, nicely covered with INTEGRAL observations, and showed rapidly changing jet orientation in the radio, interpreted as Lense-Thirring precession. This provides the unique possibility to measure polarization at different viewing angles towards a jet.
4) Is the high-energy emission of Soft Gamma Repeaters (SGRs) polarized? SGRs are highly-magnetized neutron stars (NS), but it is not clear whether the observed X-ray emission is due to the disk (largely unpolarized) or closer to the NS surface (implying high polarization).
5) Push the theoretical modelling of jet sources in terms of expected polarization, and gain analytic understanding of the physical conditions that can generate the observed polarization and its temporal evolution. (Presently there is no predictive model for the temporal evolution of high-energy polarization in jet sources.)

Beyond the scientific goals, our objectives include

6) Developing, together with ESA, a standardized format for high-energy polarization data.
7) Providing tools to enable the astronomical community to analyze observational data from polarimetry instruments
8) Preparing ourselves and the community for the next (already approved for flight) polarimetry missions.

1.2 Relation to the work programme

This proposal relates to the work programme "Leadership in Enabling and Industrial Technologies – Space", in particular the call H2020-SPACE-2018-2020, topic **SPACE-30-SCI-2020** with the **specific challenge**: ***Support the data exploitation of European missions and instruments, in conjunction, when relevant, with international missions***. We propose to take a completely new look at the data of the "International Gamma-Ray Astrophysics Laboratory" INTEGRAL, the M2 mission of the Horizon 2000 program of ESA. The INTEGRAL satellite was launched in October 2002, and is still operating successfully. In particular, we propose to concentrate on the data content, which allows astronomers to measure the polarization plane of the measured gamma-ray radiation. Both main INTEGRAL instruments provide such data, the imager (IBIS) and the spectrometer (SPI). In both cases, the analysis (including proper calibration and analysis software) has been largely neglected, despite the very high potential to gain detailed insight into the physical working of cosmic phenomena, impossible to achieve with more canonical approaches. No consensus exists upon the few published results.

The scientific importance of polarization has been recognized for a long time, as it can provide information otherwise impossible to obtain. It can be expressed via the colloquial astrophysical idiom: "but what about magnetic fields?". Indeed, the measurement of polarization via its simple two parameter description immediately provides information about the magnetic field structure, strength, and more importantly, its presence or absence in an astrophysical source. There are virtually no other ways to *directly* measure these quantities via other observables. Thus, the answer to one of the most critical questions in any astrophysical theory is locked in the measurement of polarization. Examples include understanding the partitioning of energy in GRB outflows between matter, radiation and magnetic fields, or as the ASTRONET and ASPERA roadmaps for European Astrophysics and Astroparticle physics phrase it: "to understand the astrophysics of compact objects and their progenitors, particularly the functioning of supernova explosions and gamma-ray bursts". Great advancements have been made in examining these objects via spectroscopy, but degeneracies in these analyses can only be broken with a polarization measurement.

> **Polarization** is a property of electromagnetic waves: it specifies the geometrical orientation of the oscillations. In electromagnetic waves such as visible light or γ-ray radiation, the oscillating electric and magnetic field are always perpendicular to each other. By definition, the "polarization" refers to the oscillation plane of the electric field.
> **Linear polarization:** The electric field oscillates in a single plane. We measure two quantities: the degree of polarization (between 0%-100%) and the polarization angle (between 0^{o} - 180^{o}).
> **Changing polarization angle**: This single plane changes orientation in time.
> **Circular polarization:** the speed of the angle change is constant in time. Circular polarization has been measured from the Sun, but is rare in other astrophysical sources: it is not covered in this proposal.
> **Nomenclature in this project:** we only study linear polarization, i.e. we will refer to (un)polarized electromagnetic emission (photons) from astrophysical phenomena.

Our proposed analysis and objectives conform to the **scope** of the SPACE-30-SCI-2020 call in several ways:

1. **Exploit European space data:** our proposed activity will cover the exploitation of all available INTEGRAL data of the instruments IBIS and SPI of all sources bright enough that a polarization analysis returns a significant result (positive or negative). The data are freely available from the ESA archive as well as the international

INTEGRAL Scientific Data Center (ISDC) in Geneva, except for the most recent 12 months proprietary period.

2. **Add scientific value:** Previous polarization analysis was performed by several groups, employed many different methods, and used different data selection schemes. In many cases, the published results are not only not statistically significant, but in many cases not trustworthy. With our new methodology we anticipate that many previous “polarization detections” will go away, but that trustworthy and reproducible results obtained with a coherent approach and using our newly-to-develop, but then publicly available software, will push our understanding and pave the way for future missions. We expect a major scientific advance, based on the 17+ years of INTEGRAL data as well as other instruments with polarization measurement capabilities, which will be published in a timely manner in refereed astrophysical journals.
3. **Develop new tools:** We will develop a standardized format for polarization data and corresponding response files, and will propose (and make publicly available) an easy-to-use system for analysis of future polarization data (akin to XSPEC for X-/gamma-ray spectroscopy). In addition, we will build a new Online tool that will allow users to evaluate in selected systems the most probable magnetic field configuration which can generate the observed polarization and how it changes with time.
4. **Employ new methods:** We will complete and bring to perfection our newly developed method of fitting spectra and polarization at the same time. This also allows us for the first time to perform joint fitting of data from different instruments, thus increasing the significance of any signal. This will dramatically enhance the impact of our project.
5. **Combine with other data sets:** Combination and correlation of the analysis results of INTEGRAL data will be done with measurements of the same sources performed worldwide at other wavelengths.
6. **Prepare future missions:** The new scientific and methodological insight obtained by our proposed activity will boost the preparation and scientific exploitation of the next 2 major, international satellite missions exclusively dedicated to polarization measurements, namely IXPE (launch in 2021 with Italy a major partner) and POLAR-2 (launch in 2024 with Switzerland, Poland and Germany as major partners) as well as the Sino-European mission eXTP (launch in 2027, with participation of 8 European countries). Our data analysis tools, methodology and theoretical modelling will provide a robust preparation for reaching a completely new polarization horizon.
7. **Support European science:** Together with the newly developed tools and a comprehensive description of the new methodology we plan to make all results (and high-level data products) available through ESA’s INTEGRAL data archive.

Sources emitting polarized high-energy (~1 keV – TeV) photons:
Pulsars: magnetized, spinning neutron stars in the emitting pulsations of photons via a yet unspecified mechanism.
Gamma-Ray Bursts (GRBs): the most powerful cosmic explosions, produced by the collapse of massive stars to black holes (long-duration sub-class) or by the coalescence of two neutron stars (short-duration).
Microquasars: X-ray binaries in our Galaxy with a stellar-mass black hole accreting matter from its companion star, and ejecting relativistic jets.
Active galactic nuclei (AGN): super-massive black holes at the centre of galaxies which are actively accreting material.
Soft Gamma-ray Repeaters (SGRs): X-ray sources in our Galaxy believed to be neutron stars with the strongest magnetic field in the Universe.

1.3 Concept and methodology

(a) Concept

i) Overview of Concept

a) <u>Applying new data analysis method</u>
The core concept is to take the wealth of data collected by a variety of polarization measurement capable instruments and apply our developed analysis techniques. This entails proper statistical methodology allowing for low count analysis, including in the time-resolved regime. We further extend this to the simultaneous spectral and polarization regime to gain information about the microphysical processes generating the emission as well as the geometry and magnetic field structure of the macrophysical processes.

b) <u>Applying new multi-instrument data modelling concept (3ML)</u>
The concept of our analysis method is wrapped into our 3ML framework (Vianello et al. 2015, arXiv:1507.08343) allowing for complex, multi-dimensional, multi-instrument, statistically sound data analysis. The multi-instrument nature additionally allows for more detailed measurements than those possible when analyzing the data separately. 3ML is a framework developed to directly model all data simultaneously with a joint likelihood in each dataset's appropriate space. As a hub for data collection, interaction, and modeling, 3ML provides the ideal vessel for these concepts to improve upon and extract the maximal amount of value from existing instruments. The open-source nature of this project allows for the entire community to interact, improve upon and disseminate the concepts embedded in our project.

c) <u>Analyze all suitable INTEGRAL data</u>
Analysis of gamma-ray bursts or other short-duration transients has commonly be considered to be easier targets for polarization analysis because the emission is bright relative to the background, and thus the background treatment was considered to have little impact on the result. With our thorough and rigorous background treatment, this is not a valid argument anymore. Thus, we plan to look at all sources for which (i) previous polarization analysis attempts have been made, and (ii) theory suggests polarized emission and which are bright enough to promise a detection. The INTEGRAL mission is the best-suited astronomical mission for this kind of analysis, since three different polarization detection methods are available, and thus allow us to cross-check the instrument response and software quality with a given source. While two of these polarization detection methods are well-known and have been utilized, we herewith propose to also develop a third method which relies on inter-ISGRI detections only.

d) <u>Push theoretical studies</u>
We intend to use our numerical tool to build a better understanding of the conditions that lead to the creation of polarized light in various astrophysical systems. The tool will also be publicly accessible via an online system and will be connected to the database of the observations in this proposal. It will allow the users of the database to fit for themselves the different system parameters that can generate the observed emission and polarization, including its evolution with time.

e) <u>Apply new theoretical insight to possibly new observational results</u>
Obtaining polarization data with low signal to noise and with large enough sampling in the time domain will help us better constraint the physical conditions in the emission regions of the systems we observe. This in turn will allow us to rule out some of the available models for those systems. For example, obtaining a high polarization degree in the prompt phase of

GRBs may indicate a large component of the magnetic field being perpendicular to the line of site with some averaged preferred direction. This can help us constrain the geometry of the system and the formation and amplification mechanism of the magnetic field at the shock front.

f) Link to national or international research
We have contacted the INTEGRAL IBIS and SPI instrument teams, but could not convince more partners to join this project, implying that there is no coherent polarization analysis concept at the ESA mission level. On a broader scale, there is the Integrated Activities for High Energy Astrophysics (AHEAD) project funded under the H2020 Research Infrastructure Program, recently accepted for another funding period. While their main goals are to provide access to large European infrastructure and to support technology development in High Energy Astrophysics, one of the sub-topics is the support of cross-calibration activities and simulation studies (http://ahead.iaps.inaf.it/?page_id=22). We plan to reach out and make use of any possible synergy with their planned activities re. INTEGRAL. Since polarization studies are not a topic in the new proposal (and also have not been in the previous one), we expect instrument calibration to be the only area of potential synergy. With MPE and UNIGE being partners in AHEAD, we can guarantee close connections and optimal use of opportunities.

Klein-Nishina cross-section

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{4}\left(\frac{E_1}{E_0}\right)^2\left(\frac{E_0}{E_1}+\frac{E_1}{E_0}-2+4\cos^2\Theta\right)$$

with r_o^2 the classical electron radius, E_0 and E_1 the energy of the incident and scattered photon, respectively, and θ the angle between the photon polarization angle before and after the scattering. For an initially unpolarized beam of photons, the scattered photons will be partially polarized. For polarized photons this results in the photon angular distribution after scattering not being symmetric around the initial photon momentum.

ii) State-of-the-art of high-energy polarization studies

(1) Measurement method

Pre-POLAR(-1): To date, dedicated and non-dedicated polarization measurements at high energies have relied on the measurement of photon Compton-scattering angles to infer the polarization of an observed source. The Klein-Nishina differential cross-section (see Box) depends on the energy ratio between the scattered and initial photon (epsilon), as well as the polar (θ; also Compton scattering angle) and the azimuthal scattering angle (Φ). The latter is defined as angle between the scattered photon and the polarization vector η in the plane of the detector/pixel array (see Fig. 1). Any non-zero polarization amplitude of a γ-ray source will thus alter the expected distribution of angles from pure Compton scattering. For small energies (~< 500 keV), this effect

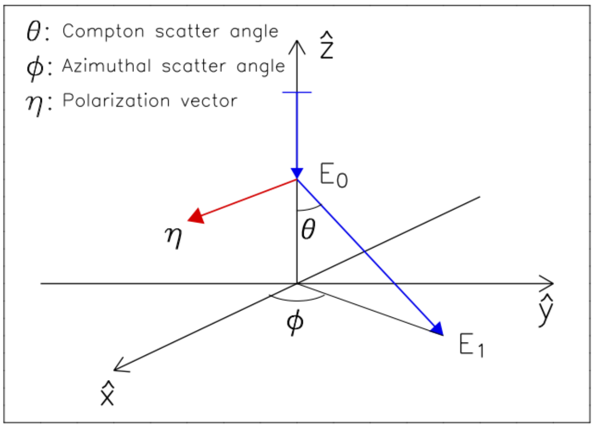


Figure 1: Scheme of scattering angles and polarization vector on a detector array (x-y-plane). [From Kalemci et al. 2004, in Proc. 5th INTEGRAL workshop, ESA SP-552, p 859]

provides the largest modulation, and becomes more and more isotropic for energies above 1 MeV (see equation in Box). However, for very low energies (~<50 keV, depending on detector material), the absolute interaction probability is dominated by photo-absorption so that the polarization sensitivity decreases in general terms.
While a relatively simple concept, in practice, the measurement is difficult: it is plagued with unknown backgrounds, instrument systematics, and weak signals due to the rarity of a photon Compton scattering within the detector. The production of well-calibrated instrument responses is computationally expensive, requires dedicated specialists, and often relies on non-existing extensive ground-based calibration. This has led to a variety of ad hoc methodologies for extracting, analyzing, and comparing polarization signals to models. Moreover, these ad hoc methods typically lead to closed-source software approaches that lack comparative studies by competing teams leaving any claim of measured polarization open to untestable scrutiny. Data and auxiliary files (such as response matrices which are always in an ad-hoc format) related to these studies are often private, even if taken from public repositories, as the extraction process is performed with proprietary software. As a result, while a number of polarization studies have been attempted in the past, also with different instruments, the scientific impact was very small due to the diversity and non-reproducibility of the results.

POLAR(-1) was a classical Compton-scatter polarimeter, built in part at Geneva University and flown on the second Chinese Space Lab in 2016/2017. It returned amazing data on the gamma-ray polarization of GRBs. While the first analysis of the brightest GRBs was done in the classical way (Zhang et al. 2019, Nature Astron. 3, 258), the instrument was built solely for polarization measurements, and thus was properly calibrated on ground (Kole et al. 2017, Nucl. Instr. & Methods in Phys. Res. 872, 28). In a second step, two additional analysis methods were tested: (i) a combined fitting of polarization (from POLAR) and spectral (from Fermi/GBM) information, and (ii) the use of the 3ML framework (Vianello et al. 2015, arXiv:1507.08343) with its modelling capabilities, including proper error propagation (Burgess et al. 2019, A&A 627, A105). This our earlier work provides the basis for this proposal, and the confidence that we are capable of fulfilling our promises.

(2) Deficiencies in previous polarization analysis

The previous polarization analysis methods are very diverse, and the problems are often hidden in the details of each individual measurement method and/or instrument used. A thorough summary of problematic data analysis issues is given by McConnell et al. (2017, New Astron Rev 76, 1), and a criticism of the conceptual (e.g. background) and/or statistical treatments is given in Burgess et al. (2019, A&A 627, A105), which we shortly summarize below.

Measurement principle and proper statistics: Until recently, the current state-of-the-art in the analysis of high-energy polarization data relied heavily on developments in the field of optical polarimetry (cite Vaillancourt 2006, PASP 118, 847). However, this notably different measurement regime differs from high-energy polarimetry in two distinct ways:

1) Polarization degree and angle are measured indirectly in high-energy astronomy. In the field of optical polarimetry, via the use of linear polarizers, the degree and angle of polarization are directly measured and thus not parameters to be estimated from the data. Conversely, in high-energy astronomy, measurements suffer the classical inverse problem, i.e., the polarization degree and angle are convolved with the non-invertible instrument

> **Likelihood:** The statistical function that compares the distance of model predictions to the observed data.
> **Chi^2 (χ^2):** a shorthand for the logarithm of a Gaussian likelihood.

response during the measurement process. Thus, the measured signals are related to, but indirectly, the true polarization parameters. Such an impediment to measurement requires a statistical deconvolution of the signal from the response via a process referred to colloquial as forward-folding and formally as the Backus-Gilbert method. The process involves proposing a model in its true signal space, convolving that model with the instrument response, and then comparing this convolution with the observed data statistically.

2) The number of photons in high-energy polarimetry is in the low-count regime requiring a proper Poisson likelihood. The number of optical photons measured in optical polarimetry is high enough to invoke the so-called central limit theorem allowing for the use of the χ^2 or Gaussian likelihoods as well as the assumption of Gaussian-distributed uncertainties on the directly measured polarization parameters. This allows for several approximations in the estimation of polarization parameters, including the derivation of analytic parameter uncertainties. However, these conditions do not hold at high-energies where the paucity of signal photons does not allow for the above assumptions and analytic derivations to hold. Thus, these derivations, while frequently used in high-energy polarimetry, are not valid.

The combination of these two effects requires a proper derivation of the data likelihood for the types of measurements that the POLCA project is designed to enable. In fact, the members of the team have made progress in this aspect of the project already with the derivation of the proper data likelihood for POLAR(-1) (Burgess et al. 2019, A&A 627, 105). The project will build upon this success to derive the proper likelihoods for all instruments involved in the study.

Global issues with analysis: In order to make perfect measurements, high-energy polarimeters must be able to measure the Compton scattering angle uniformly and with infinite precision. The segmented nature of these detectors unfortunately prevents the measurement of continuous

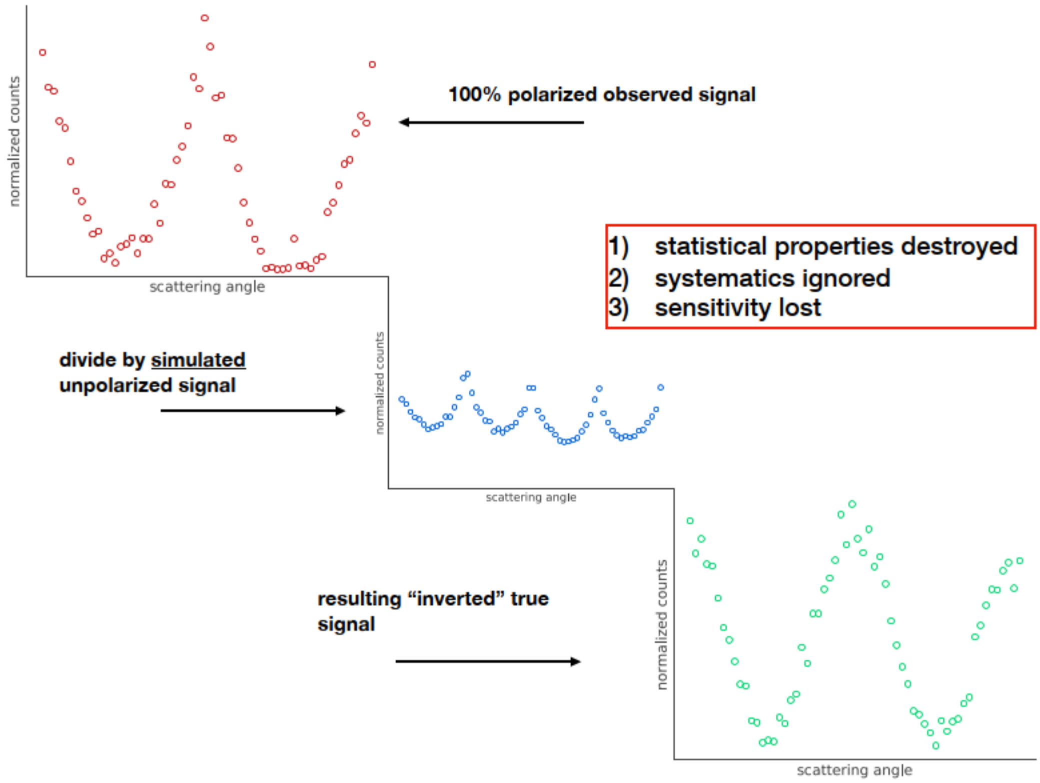


Figure 2: Scetch of standard-practice previous analysis with background subtraction.

scattering angles causing them to be descretized into so-called scattering angle bins. However, this discretization can be augmented if the polarimeter is rotated about its detector plane axis creating additional "virtual" scattering angle bins which asymptotically allows for a continuous measurement of scattering angles. Even so, any realistic instrument will imprint its detection mechanism upon the true signal causing deviations from the pure sinusoidal expected signal pattern.

Thus, a major part of previous polarization analysis has focused on removing or circumventing this pollution of the true polarization signal by the observing instrument. While differing in detail, all past approaches have adopted the method of inverting the detected signal into a pure polarization signal. These methods can be summarized with the following steps:

- A simulation of the polarized signals being detected by the instrument is created. This results in a histograms of theoretical distributions for observed Compton scattering angles in the instrument's native data space
- The observed data, in the form of Compton scattering angle histograms, are divided by the simulated histograms for the unpolarised case, thereby theoretically removing all effects with the exception of those induced by the polarization. Technically, this can be understood as an effort to invert the observed data into the true signal space.
- The inverted signal is then normalized and fit with simplistic χ^2 statistics to a sinusoidal curve, from which the polarization parameters are obtained.

While this method appears correct upon a first look, several issues with inverting must be considered. First, the instrument responses are highly singular, and numerical inversion of them is well-established to be numerically unstable. Moreover, the distribution of events into Compton bins suffers from dispersion due to both the energy-dependence of the Compton scattering and the discrete nature of the measured angles i.e., the detected bin is probablistic and no one-to-one mapping between measured and true angle can be uniquely determined. Even if such a mapping existed, the energy of the photon itself also suffers from dispersion, making it impossible to uniquely determine its true value. These effects alone combine to make direct inversion of the polarization signal impossible. This has not, however, stopped such methodology from being practiced.

Ignoring the difficulties of signal inversion can lead to several immediate issues with derived results even disregarding the statistical issues inherent in past analysis discussed below. First, inversion can lead to plainly incorrect results. As the inversion is unstable and cannot include the higher dimensions of both angle and energy dispersion, the resulting analysis can incorrectly identify features (amplitudes, phase) in the observed data as the true parameters of the signal. The instrument response will never be perfect, despite enormous efforts. Using the method described here, all imperfections in the instrument response will result in deviations in the measured distribution. These deviations, even if they are minor, can easily be mistaken for polarization signals. Moreover, these results will be arrived at with over-confidence (smaller than actual uncertainties) due to the loss of information in the true instrument response (e.g. dispersion). Thus, while the derived parameters can appear to be very exact, it is likely that they are incorrect and too certain. Finally the simulated scattering angle distributions highly depend on the spectrum of the source. Uncertainties in the spectrum will therefore lead to wrong results as well as systematic uncertainties which are difficult to determine using the classical method. Using modern analysis methods, such as those used in Burgess et al. (2019, A&A 627, 105), this problem can be overcome by fitting the spectrum and polarization at the same time.

Further complicating the issue is the use of improper statistical methodology in the estimation of polarization parameters. The above incorrect inversion technique result is pseudo polarization parameters very similar to what are measured in optical polarimeters. This leads to the incorrect assumption that the "data" are polarization variables and when in reality, the data are Poisson distributed counts in Compton scattering bins. This incorrect assumption leads to the use of the incorrect likelihood on the data. Specifically, the likelihood used derives from optical polarization with Gaussian uncertainty on the values. An issue with this classical analysis is that polarization parameters are bound to specific ranges. For example, the polarization degree is a percentage between 0 and 100. It is not statistically valid to include these bounds in the classical analysis. Thus, one often finds unphysical (nonsensical) statistical uncertainties on the polarization degree such as 90±30% (e.g. the ASTROSAT paper mention earlier). We have shown in our previous work (Burgess et al. 2019, A&A 627, 105) that this can be avoided by using proper Bayesian analysis that introduces physically principled priors.

We conclude in this section that a significant investment in developing proper analysis techniques will not only aid in more deeply exploiting existing EU instrument data, but will also add value to this data beyond what is currently available. We have demonstrated in our past work with POLAR that we have the expertise, technology, and ambition to tackle these issues and seek to further develop in this program.

(3) Theory

Photon energies between hard X-rays of 20 keV and γ-rays up to a few MeV cover the range where many of the most-spectacular cosmic sources have their peak emissivity, so that essential physical processes of high-energy astrophysics can be studied most directly. Polarized radiation can occur due to numerous processes at the source, e.g. when (1) photons are emitted by electrons in the presence of magnetic fields via cyclotron or synchrotron processes, (2) scattering at free electrons or small particles, (3) Zeeman and Stark effects, and many others, preferentially at lower energies. Thus, many sources emit polarized light, from asteroids and planetary atmospheres over normal (magnetic) stars and the Sun, to white dwarfs, pulsars, accreting binaries, and jets in AGN. While there are differences between source types, it is fair to say that for none of the astrophysical sources we have a proper theoretical model, which would explain the polarization variability. For some of the source types, we will attempt to provide such models with our project.

Polarization in the context of synchrotron radiation indicates an asymmetry in the magnetic field (a preferred directionality on the plane of the sky) or in the geometry of the emitting source. When the emitting source is moving at a relativistic velocity, the observed emission comes from a small region in the source due to relativistic beaming. Detection of polarization from such a region can point to either one of the above reasons. Tracking the temporal evolution of the degree of polarization and direction of the polarization vector (electric vector position angle) can break the degeneracy, and provides valuable information on the physical conditions at the source. In addition to the beaming effect, the boost from the emitting to the observer frame generates intrinsic rotation of the polarization angle, which needs to be taken under consideration as it complicates the interpretation.

The accepted model for the observed emission in GRB afterglows and possibly also in the prompt emission is synchrotron radiation by electrons (Rees & Meszaros 1993, ApJ 418, L59; Burgess et al. 2019, Nature Astron. 3, 471) that are accelerated on spherical-cap shaped shocks. The magnetic field on the shock can have different geometries, depending on the conditions and origin of the unshocked fluid. A large scale ordered field on the shock plane may grow in shocks that are formed in the expanding GRB flow, when a relic magnetic field of the jet engine is carried by the flow and gets boosted at the shock front. Such a field can give high polarization even if the geometry of the outflow is completely spherical. Shocks that form in the interstellar

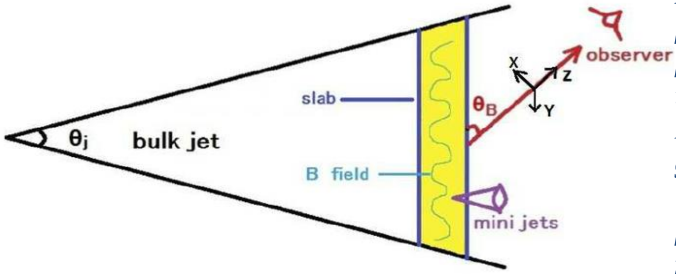


Figure 3: Sketch of the GRB prompt emission and polarization within a compressed slab. Shock propagation is in the bulk jet structure and turbulence occurs behind the shock front. Random and small-scale magnetic fields are generated by turbulence. GRB prompt emission is the total emission from mini-jets. The GRB prompt polarization is dependent on the magnetic field configuration. [From Mao & Wang 2013, ApJ 776, 17]

medium (afterglow forward shocks) will likely have magnetic fields that grow from random plasma fluctuations (e.g. Nishikawa et al. 2003, ApJ 595, 555; Spitkovsky 2008, ApJ 673, L39). These fields will have either random orientation on the shock plane or a radial configuration. Polarization from such geometries requires a symmetry breaking of the radiating region itself (e.g. due to relativistic beaming). The continuous deceleration of the shock in this case will reveal new emission zones, which were concealed before due to the beaming effect, resulting in rotation of the EVPA.

Linear polarization at a level of a few percent was first detected in the afterglow light of GRB 990123 (Hjorth et al. 1999, Science 283, 2073), 990510 (Wijers et al. 1999, ApJ 523, L33) and GRB 990712 (Rol et al. 2000, ApJ 544, 707). It inspired several theoretical models that calculated the polarization of synchrotron emission originating from relativistic AG shocks, assuming a random magnetic field configuration in the shock plane and synchrotron emission by a powerlaw distribution of electrons (Ghisellini & Lazzati 1999, MNRAS 309, L7; Gruzinov & Waxman 1999, ApJ 511, 852; Sari 1999, ApJ 524, L43). Later observation of GRB afterglows with higher polarization degrees, e.g. GRB 020405 (Bersier et al. 2003, ApJ 583, L63) was followed by models that calculated polarization from a uniform magnetic field on the shock plane (Granot & Königl (2003, ApJ 594, L83) and for a random field with patchy emission pattern (Nakar & Oren (2004, ApJ 602, L97).

Polarization in γ-rays during the prompt GRB phase was first claimed for GRB 061202 (Coburn & Boggs, 2003, Nature 423, 415) from RHESSI observations, and later by the IBIS imager on board INTEGRAL for GRB 041219A (Laurent et al. 2010, in X-ray Polarimetry, CUP, p. 230). It was followed by models that calculated the linear polarization assuming a large scale ordered field (Lyutikov et al. 2003, ApJ 597, 998) or a random field on the shock plane (Nakar et al. 2003, JCAP 10, 5; Granot 2003, ApJ 596, L17). Since then, dozens of measurements were made of polarized light with different polarization degree from both GRB afterglows as well as from the prompt emission. A list of GRBs with detected polarization in their prompt phase is given in Gill et al. 2019, MNRAS 2582). They also review the expected degree of polarization from various plausible magnetic field configurations of the shock plane. Other discussions on the expected polarization of the prompt phase from various field configurations can be found in Lazzati 2006 (J. Phys. 8, 131), Toma 2013 (arXiv:1308.57) and Nava et al. 2016 (MNRAS 455, 1594).

Scientifically, polarization results are generally considered as "curiosity" or "interesting aspect", but have not (and do not) drive(n) the astrophysical modelling of cosmic sources or the theoretical thinking. The situation is equally bad in optical or high-energy astrophysics. Our POLCA project aims at laying the foundation to change this situation (in high-energy astrophysics).

(b) Methodology

Our main methodological approach is to apply newly developed concepts (as described in the previous section) to the archival data of ESA's **gamma-ray science** mission INTEGRAL. The result of our research project is expected to serve multiple areas: (i) **gain new scientific insight** into the emission mechanism in various source types, (ii) **develop a universal data format** for polarization data which is appropriate for present-day analysis tools, (iii) **develop new methods** of data analysis with rigorous error handling and propagation, and (iv) **prepare the ground for future high-energy missions** to measure polarization which are presently under construction. Thus, in the language of science management, this is a research project which will demonstrate the superior performance of new data analysis tools, where their application to INTEGRAL data serves as a **pilot project** for the application to future science missions with the goal of substantially increasing the science return.

The basics of our methodology is shown in the figure below, and the various components are described in the following sub-sections i)—viii).

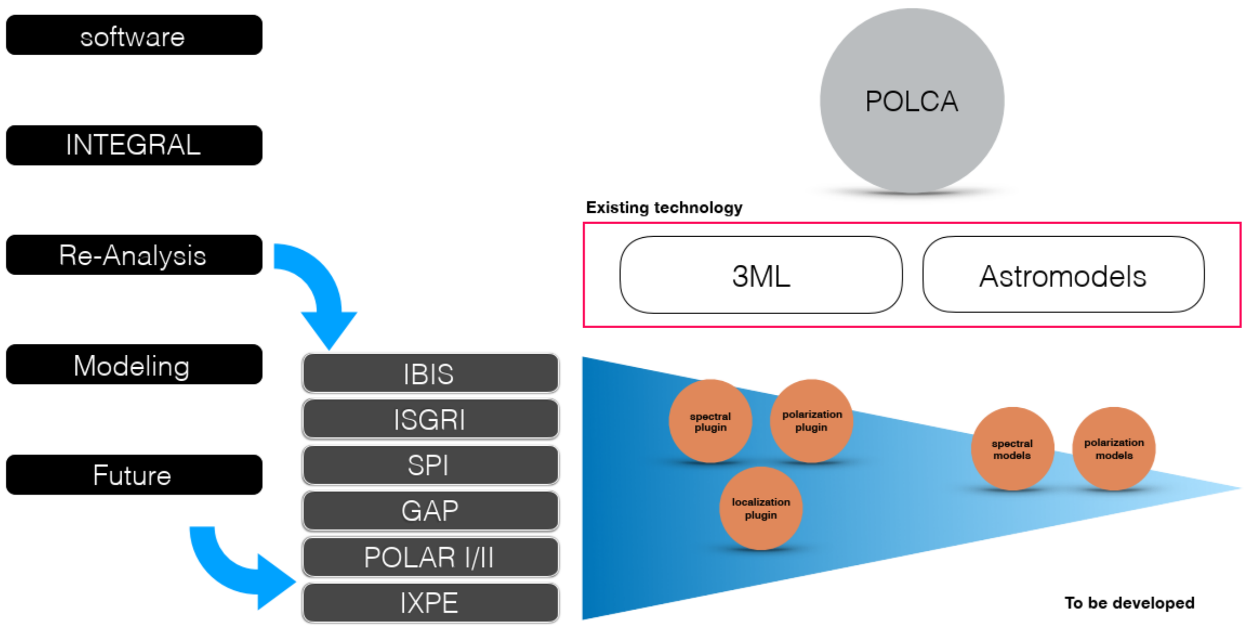


Figure 4: Scheme of the proposed methodology: using the existing 3ML framework and earlier developed Astromodels as the central hub of our software development and analysis strategy.

i) Standardized Data format

The explosion of scientific value and knowledge that has occurred over the last several decades in high-energy astronomy is due to two key innovations: common, standardized data formats and definitions as well as open-source standardized analysis software. These two concepts enable astronomers to test theories against data from multiple instruments without the burden of deep instrument knowledge and low-level processing. Key examples of this are the generic OGIP (Office of General Investigator Program) X-ray FITS (Flexible Image Transport System) file formats which are easily read by the open source XSPEC software and the Fermi GT science tools (https://fermi.gsfc.nasa.gov/ssc/data/analysis). Instrument teams release their data in the formats required for the analysis tools, and then astronomers readily test their models against the data in a proper way. The success of these tools to enable science can be measured in both the citations to the tools and the number of papers written by external scientists using these high-energy instruments. Thus, building such a framework for the polarization data will lead to the same explosion of data use by existing ESA/EU missions addressing a key component of this RIA call ("**advanced processing of data**"), as well as more generally the mission of ESA to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world.

The POLCA project will leverage from the heritage of high-energy spectroscopy to:

- **Define/propose a standardized format for high-energy polarization data.** Using the team's expertise as well as consultation with field experts, we will develop a data format and storage system that will allow for instruments with polarization capable data to disseminate these data in standardized form. The processing tools developed within the project will be open-source and provided to instrument teams fully documented and unit-tested. Similarly as the standard ARF/RMF formats make it easy for everyone to analyze spectroscopic data, our response format will provide the same ease for polarization analysis.
- **Create multi-mission public analysis tools which interact with this data format.** Even if data are standardized, a framework for the proper analysis of the data must be defined and created. We will leverage our experience in developing multi-mission data analysis and modeling tools to create a user-friendly open-source framework enabling novice to expert astronomers to interact with and model polarization data collected with various instruments.

The considerations of defining a standardized data format must include the following components:

- ✓ **Interpretability:** Any data format defined must be readible/serializable to enable quick understanding of its content, size, and validity. Examples of interpretability can be found in the ASCII-based text headers of FITS files. These allow astronomers to understand the contents of data on any system even when FITS reading software has not been installed.
- ✓ **Access to software tools** to read/manipulate/store the data: A data format that lacks open-source tools to read and operate on the core data product is useless to astronomers outside of instrument teams. In order to disseminate and broaden the use of data to the largest possible user-base, a format must be designed such that the tools available to read and operate on the data are easily obtained, stable, and have an active development team.
- ✓ **Flexibility:** While the goal of the POLCA project is to fully exploit the capabilities of existing and past instrument data, considerations must be made for the capabilities of future observatories which may require more parameters, larger data, etc. to adopt the data format such that past and future instruments can have their data analyzed in consistent, tested manner. Examples of where this is important include the FITS file format. As datasets have become richer and larger, the FITS file format has troubles adapting to the speed, and parallel capabilities of modern computer systems. However, the heritage of FITS in astronomy should be considered as it is the standard of most instruments.
- ✓ **Longevity:** In order to maximize the long-term use of existing data, any data format must have both a history of use as well as an active team of developers which will enable its maintainability many years after the instrument generating the data has stopped working.

In order to address these issues, the POLCA project will examine the current status of data formats in high-energy astronomy and weigh their pros and cons. Additionally, consultations with our partner Advisory Board will help us to ensure that our proposed data format will be applicable to the current and future goals of ESA as well as the community at large. An investigation of modern and past data formats will be undertaken to understand whether we will adopt proven and widely used storage systems such as FITS or opt for modern formats with richer capabilities such as HDF5. Investigations into more modern formats for data storage are a subject of much research for future instruments (e.g., Greenfield et al. 2015, Astron. & Computing 12, 240). Formats such as the Advanced Scientific Data Format (ASDF) allow for more detailed data descriptions which can greatly enhance this project's ability to store the large amount of information required for polarization studies.

ii) The 3ML framework

An important objective of the POLCA project is enabling the astronomer community at large to easily access and model the data from instruments which measure polarization. This requires a well-tested, user-friendly interface between data, models, and proper statistical likelihoods. Such a framework exists in the Multi-Mission Maximum Likelihood (3ML; Vianello et al. 2015, arXiv:1507.08343) framework **co-developed by a team member**. 3ML provides an abstract data interface via plugin system where instrument teams or individuals create an interface to the data by specifying the way in which a spectral/temporal/spatial model interacts with the instrument's data likelihood. Thus, an end-user only needs to provide the specific data and model for the analysis at hand, combine them in the plugin, and compute the model inference via either sampling or optimization techniques (see Fig. 5). As this framework exists and is used by several instrument teams (Fermi, HAWC, POLAR), the project will design generic and specific polarization plugins which will link existing data to the models developed within POLCA.

A subsequent impact of integrating the polarization capabilities of various instruments into the 3ML framework will be the automatic ability to combine polarization analysis from different instruments as well as with other information including spectroscopy. Therefore, models that include both polarization and energy in their predictions can simultaneously be fitted to data (even from different instruments) covering both of these axes.

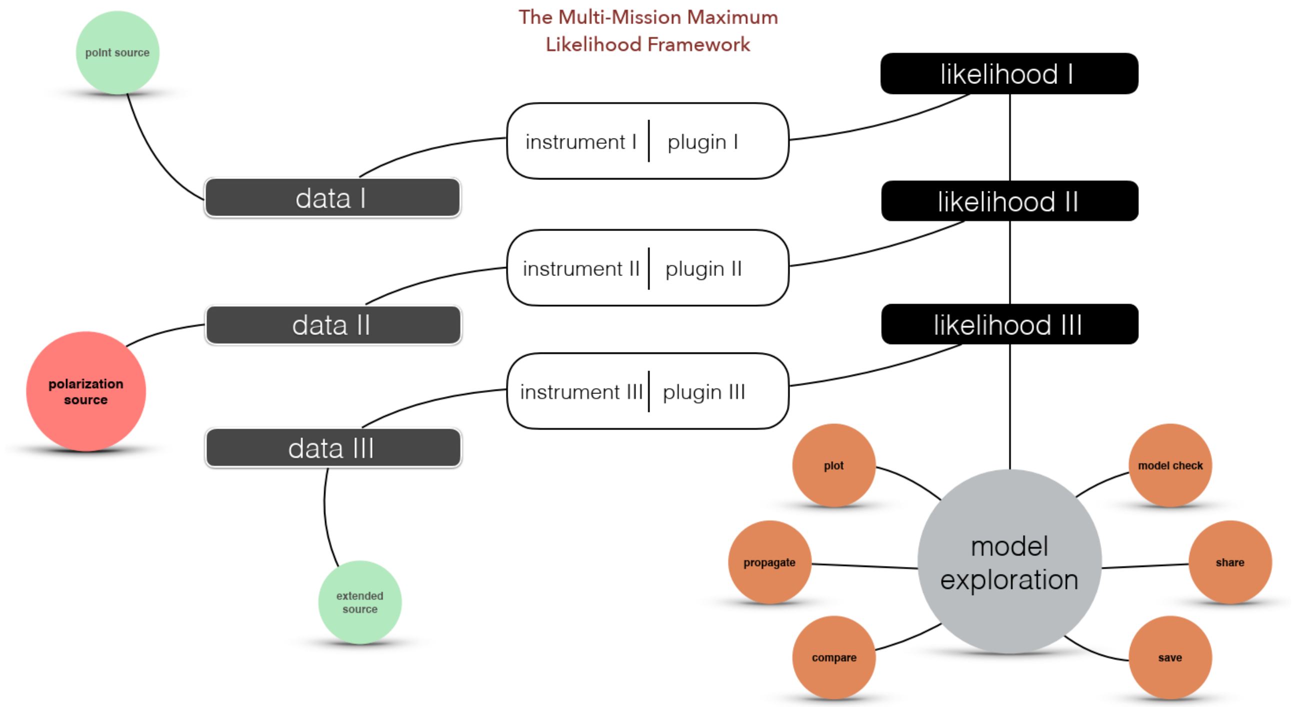


Figure 5: Visualization of the 3ML framework. The schematic shows the high-level concept of 3ML where different astrophysical sources with possibly different messengers generate data, which is connected to each instrument's specific data likelihood via a plugin. Then, model configurations (parameters) are explored via the users preferred sampling tools.

iii) Data Analysis Concept

(1) Pushing boundaries

By combining our innovative data analysis framework with our instrumental calibration for polarization, we will enable the ability to push polarization analysis to new levels to fully exploit the information contained in the data.

(1.1) Time-resolved polarization

Our team has already demonstrated that the use of proper statistics and calibration allows for existing data to be analyzed in a time-resolved manner to much higher precision (compare Kole 2018, arXiv:1804.04864; PoS(MULTIF2017) to Burgess 2019, A&A 627, 105). As time intervals are made finer, the number of observed events drops. The use of classical methods requires the data to be temporally binned such that the number of events is high enough to apply asymptotics. Thus, a trade-off is made between resolution and so-called sufficient statistics. If this approach is followed, then time-resolved analysis will never advance as the number of photons is limited by the source.

To resolve this conflict, we will employ proper counting statistics likelihoods derived from Poisson distributions that are not limited by asymptotics. These likelihoods are valid even when no photons are detected in a time/energy/scattering bin. Thus, data can be sub-divided into arbitrarily small time intervals fully exploiting the critical temporal evolution of the polarization parameters.

The lack of signal at high-temporal resolution does, at first look, imply that while we can obtain information at a high temporal cadence, this information will be statistically uncertain (large error bars). To address this issue, we will rely on our development of time-resolved polarization models. Rather than simply analyzing individual time slices, we will use our models to link information across time thus providing tighter predictions.

Therefore, we will ambitiously push the temporal boundary currently faced by the field.

(1.2) Energy-resolved polarization

Different physical processes arise in sources at different energies. As an example, GRB emission could be dominated by thermal emission at high energies, and synchrotron emission at low energies (e.g. Lundman et al. 2018, ApJ 856, 145). Just as these two processes imprint different shapes on the spectral distribution of photons at different energies, they will also produce different polarization signatures at different energies (see Fig. 6). The ability to simultaneously analyze both dimensions in the data provides the ability to test richer models, have tighter constraints on parameters, and fully exploit the information of every detected photon by existing instruments.

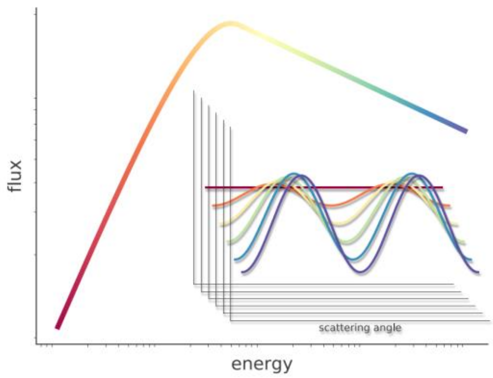


Figure 6: Schematics of energy-dependent polarization: different parts of the high-energy spectrum can have different degrees of polarization. For instance, synchrotron emission is predicted to be much stronger polarized above the cooling frequency.

To enable this capability, we expand upon our approach of forward-folding (Fig. 7) both the polarization and spectral model through the response of the instruments in our project. However, we will further subdivide the scattering bins to fully account for their change as a function of energy. Thus, an individual scattering bin will have a fully detailed spectral response. The results will be that after an analysis, a signal can be decomposed into polarization parameters that are a function of energy.

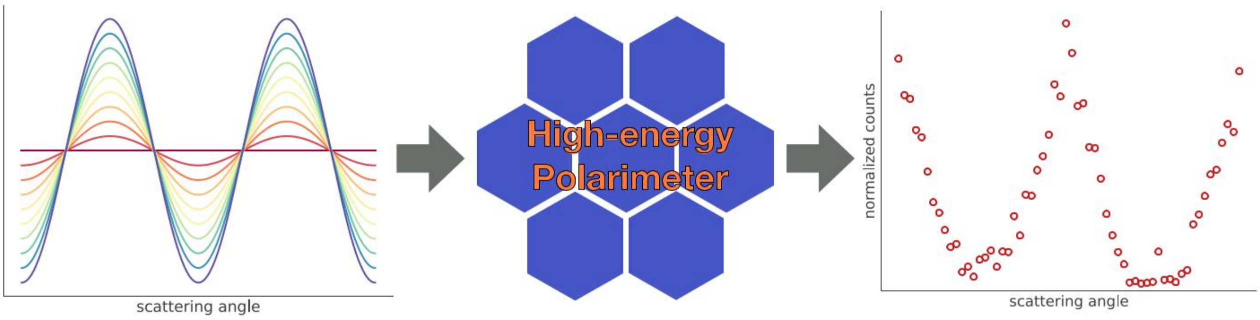


Figure 7: Scetch of the proposed proper forward-folding method for the generation of the polarization response (not the data analysis).

(2) Polarization response

The translation of an astrophysical polarization signal into an instrument's electronic data space is encoded in a response function. X-ray polarization signals are encoded in the data via their energy-dependent Compton scattering angles. Due to the finite nature of recording these angles and energies, polarization suffers from dispersion, i.e., a non-unique mapping from data to the original signal. Thus, it is impossible to invert this response function to recover the original signal. This leads to the process of forward-folding which is the established practice in X-ray spectroscopy. For X-ray polarization this entails a convolution of a proposed polarization signal with the response, which mathematical converts the signal into the space of the recorded data. While this process is standardized in spectroscopy, both the process for using this response and its data format are not universally defined for polarization.

The design of the response for Compton-based polarization instruments can be cast as three-dimensional matrix. The axes of this matrix are as follows:

- the true spectral energy
- the polarization degree and angle
- the measured scattering angle

As these response matrices can contain many elements, and often also depend on instrument-related details (instrument coordinates, energy dispersion, angular resolution), a clever data format and storage needs to be designed. For example, the polarization response intends to describe deviations from a non-polarized source, i.e. how the scattering angle distributions vary as a function of polarization angle and degree. However, many instruments do not measure the scattering angles directly, but record a characteristic change in their native photon-counting data space. Any extraction of polarigrams will be flawed as individual instrument designs and the nature of Compton scattering are ignored. An example is shown for the SPI telescope aboard INTEGRAL in the next sub-section.

Another main task will be investigating the heritage of spectral response storage and leveraging `calibration'. Similar to the imaging and energy response, the additional polarization dimension requires an absolute gauge for each instrument. While many astrophysical sources are expected to show polarized emission in the soft gamma-ray band, the true emission spectrum as well as the true polarization (as a function of energy) is hardly known for any source. The Crab Nebula is the classical calibration source as the absolute flux at hard X-rays has been shown to vary only by ±5% over a time period of ~10 years (e.g. Wilson-Hodge et al. 2011, ApJ 727, L40), and the spectral index is also stable (e.g. Jourdain & Roques 2009, A&A 704, 1). It turns out that also the polarization parameters of the Crab appear constant over time and energy (e.g. Jourdain & Roques 2019, A&A 882, 129), at a degree of 24% and an angle of 120º. As the measurements from different instruments coincide, the Crab Nebula can be used as a 'standard protractor'.

In order to calibrate, and later consistently calculate the response, a large amount of simulations is required: As an example we note that for POLAR, a response for a single GRB with sufficient statistics took 1 day to produce on a cluster with ~100 cores. This implies that each zenith/azimuth location takes about one day on such a cluster, a full response would therefore take about half a year - per instrument. While this is manageable, it certainly requires (and has room for) considerable optimization.

Typically the response of an instrument is produced using Monte Carlo (MC) simulations in which the instrument and its electronics are modelled as good as possible. As some of the parameters which are used in the MC simulation are not perfectly understood, the final response will not be perfect either. The uncertainty on the final response due to the uncertainty on some of the simulated parameters is often neglected or, at least in the field of high-energy polarization, added artificially. To use POLAR as an example: uncertainties in a range of parameters such as the light yield of the scintillators, the gain of different parts of the electronics or the width of thresholds lead to uncertainties in the final polarization response. In order to take this into account, simulated scattering angle distributions were compared with those measured during dedicated on-ground calibration tests. The difference between the measured and simulated curve was taken as the final uncertainty which was then artificially added to the response.

Although the above described method attempts to take the uncertainties into account, a range of problems can be found with this method. Most importantly, on-ground calibration tests typically just allow to test the response of a discrete set of spectra, polarizations etc. and therefore will not allow to understand the systematic uncertainties for each physical source measurement. Secondly, the uncertainties are added, while instead the measurements can be used to mitigate uncertainties, thereby reducing the systematic errors in the response and therefore in future data analysis.

For this purpose, a range of responses can be produced as a function of the different uncertain parameters (for example the scintillator light yield in POLAR). Subsequently, using a range of both on ground and in-orbit calibration measurements, one can fit all the different components, thereby optimizing the final response. Such a method has previously been used in Xu et al. 2014 (ApJ 794, 97). The final remaining uncertainty can later be naturally incorporated into the response, allowing to take instrument induced systematics directly into account in the analysis, and removing the need for adding artificial uncertainties.

While such a method allows to improve the data analysis, performing such simulations can be time consuming. Significant studies therefore have to be performed in order to optimize such studies and incorporate the method properly for high -energy polarimetry responses.

(2.1) SPI

SPI is a coded-mask spectrometer-telescope which utilizes a hexagonal 19-element, high-purity Germanium detector (6 cm thick) array in a honeycomb configuration. It is sensitive to photons in the energy range between 20 and 8000 keV, with a spectral resolution of ~2.1 keV at 1 MeV, and a field of view of 16x16 deg^2. While SPI is not a classical Compton telescope, it can still be used for Compton polarimetry since also multiple scatters are recorded: For example, Compton scattering of a photon from its initial interaction detector into a neighboring one where it is photo-absorbed would be termed a double-event, if this falls into a 350 ns coincidence window. Due to the geometry of SPI, there are 42 of these 'double detectors', which would define six possible azimuthal scattering angles.

However, SPI is not measuring these angles as no ‘Compton reconstruction’ is performed. Instead, the 42 double detectors include all the information required to determine the polarization parameters of a source in the above-described full-forward modeling approach (see Fig. 7). Based on previous simulation studies (Kalemci et al. 2004, in Proc. 5th INTEGRAL workshop, ESA SP-552, p 859; Kalemci et al. 2007, ApJS 169, 75), it has been suggested that the modulation for SPI is in the range between ~30 % for 100 keV photons to ~15 % for 600 keV. In terms of the polarization response for SPI, polarized sources will change the expected photon count pattern of ‘double-detectors’ which would naturally be dominated by the mask’s coding (determining the position of the source), and Compton scattering.

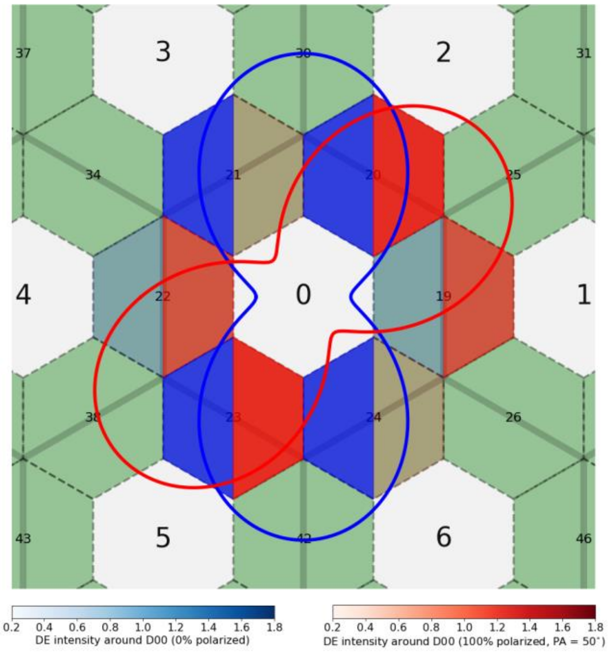


Figure 8: SPI detector array (numbered hexagons) and the differential Klein-Nishina cross-section (red/blue).

A visualization of this transformation is provided in Fig. 8: Here, the SPI single detector array (numbered grey hexagons, thick boundaries, 0–18) and the definition of double detectors (green, dashed boundaries, 19–60) is shown. The differential Klein-Nishina cross-section is indicated for a source, emitting at 500 keV, either unpolarized (blue solid line) or 100 % polarized (red solid line; PA = 50 deg) - both as seen with a Compton scattering angle of 90 deg. The six neighboring detectors of detector 0 (i.e. 1–6) result in six pseudo-detectors, numbered 19–24. Depending on the polarization degree and angle, the relative pseudo-detector count rates (blue and red shading) change. This is shown for the case of detector 0 and its neighboring detectors only: The instrument-specific data space of ‘counts per (pseudo-)detector’ is clearly seen , as for a specific energy and Compton scatter angle, the neighboring detector share un-equal amounts of scattered photons. This asymmetry is enhanced by a polarized emission, and leads to a different expected count rate for each double-detector. As the Compton scattering angle is not measured, different values ‘overlap’ in the SPI data space, and also scatterings from other detectors imprint their patterns in the limited, 42-element data space. This total relative change is stored in the polarization response, for each aspect angle and energy.

It must be noted that especially at hard X-ray and soft γ-ray energies, the instrumental background from cosmic-ray interactions in the instruments and satellite material is contributing typically more than 99% of the total measured counts. This must be taken into account in a proper statistical analysis - in particular when the background is determined from an independent data set (e.g., before and after a GRB). For persistent sources, a widely applicable background model has been developed at MPE (Diehl et al. 2018, A&A 611, 12; Siegert et al. 2019, A&A 626, 73) and tested for different sources using SPI’s single events. An extension of this background modeling method to multiple events is straight-forward, but requires testing and validation.

Changing instrument parameters require separate (spectral and) polarization responses: During the 17 mission years of INTEGRAL, four out of 19 SPI detectors failed at different times until 2010. Such a dead detector modifies the expected response dramatically because initial double events, scattering in a dead detector, will be counted as single events in the neighboring detectors. This has to be taken into account as it might falsely be interpreted as a possible polarization signal. Thus, for each camera configuration of SPI, an individual response is required.

Finally, the SPI polarization response includes the following dimensions for each camera configuration as imprinted in the relative counts in each 'double detector': Source position (zenith/azimuth), initial and scattered photon energy (energy redistribution matrix), polarization parameters degree and angle.

(2.2) Standard IBIS approach

The INTEGRAL/IBIS instrument is a coded aperture telescope with a dual detection layer. The top detector, ISGRI, consists of 128x128 CdTe pixels for the energy range up to 1 MeV (Lebrun et al. 2003, A&A 411, L141). The lower detector, PICsIT, comprising 64x64 CsI scintillation pixels, operates in the 190 keV – 10 MeV range. In the so-called Compton mode, photons are scattered from a CdTe pixel in the IBIS plane to the PICsIT plane, appearing as two events at the same time. The measured quantities are the deposited energies and the two 2D coordinate positions in each detector. The direction of the incoming γ-ray can be confined to an event circle determined by the base of the cone with its opening angle Φ, with the axis defined by the connecting line between the two detector plane coordinates. An inherent problem is that the mask imaging is a statistical deconvolution, so cannot be used at the same time as Compton imaging. For the polarization analysis, two properties are important: (i) the energy resolution, as it determines the Compton scatter angle, with the resultant modulation being angle-dependent, and (ii) the number of background events, as it determines the rate of accidental coincidences. In practice, the energy resolution of about 20%-25% (FWHM) is acceptable, but the background rate in PICsIT is so large that the proper selection of true Compton events is a very delicate process (and prone to errors).

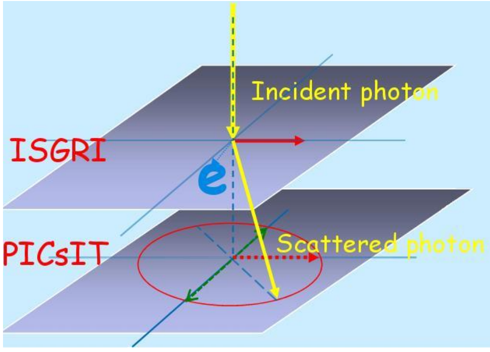


Figure 9: Schematics of the Compton scattering between the two IBIS sub-detectors ISGRI and PICsIT [From Laurent 2017, talk at Hiroshima Conf., Feb. 2017].

Following the above approach with SPI, a forward modeling approach including the complete response to be applied to the combined 'Compton mode'-IBIS data is needed: This requires simulations of the full IBIS configuration, i.e. the mask, ISGRI, and PICsIT, to obtain the expected counts per pixel, just as in the ISGRI imaging response, but including the polarization parameters as well. This allows an energy-dependent polarization analysis (see the previous sub-section 2.1) without the intermediate step of extracting scattering angles, which is in itself uncertain (Zoglauer & Kanbach 2003, SPIE 4851, 1302).

The IBIS 'Compton mode' response for polarization is thus made of different 'images' (relative pixel counts) for ISGRI and PICsIT as a function of source position (zenith/azimuth), incident and scattered photon energy (dispersion matrix), as well as the polarization parameters degree (Pi) and angle (eta).

(2.3) New ISGRI-only approach

As described above, typically only one measured quantity is used for analyzing high-energy data. Especially in the case of ISGRI with its mask coding and sub-module geometry, the timing information will provide additional discriminative power with respect to measuring polarization. The timing between individual events allows us to identify Compton scatterings inside ISGRI alone: Only the time differences of events that accumulate close to zero would be chosen to identify (select) possible Compton events. Furthermore, for pixels at the edges or corners of the sub-modules (see sketch in Fig. 10), only the opposing side will potentially be populated by Compton events (as the boundaries are 'dark'). However, since the mask also blocks certain neighboring pixels, other neighboring pixel events cannot be due to Compton scattering. This applies to several pixels along the edges of ISGRI's sub-modules, and would then provide again a distribution of Compton scattering angles (counts per azimuthal scattering angle bin), translating the initial measurement (counts per pixel and time modulo mask).

A full forward modeling of this detailed data selection is challenging but will provide both, a cross-check between the classical IBIS 'Compton mode' and SPI polarization measurements, and a new approach to utilize the measured quantities directly, and infer polarization parameters directly. Simulating such a response will result in pixel patterns for near-edge pixels as a function of source position, photon energy and redistribution, and polarization parameters.

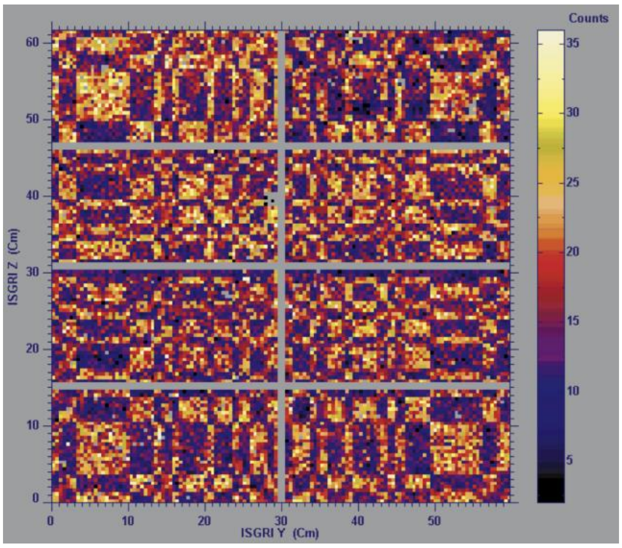
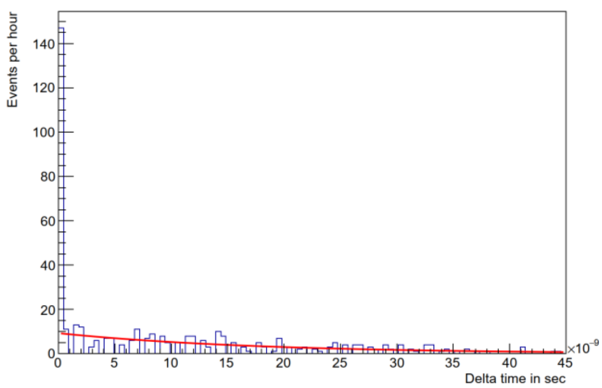


Figure 10: ISGRI shadowgram of an ~on-axis source (Lebrun et al. 2003, A&A 411, L141). The ISGRI detector consists of 8 blocks (separated by the grey lines in the figure). Our newly proposed ISGRI-only mode uses those photons which are Compton-scattered by 90^o over these block boundaries (see Fig. 11).



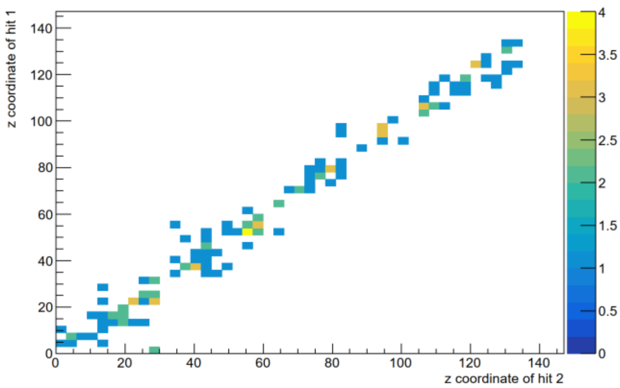


Figure 11: Distribution of events in ISGRI between the left three blocks and the right 3 blocks (see Fig. 10), taken from one single science window. ***Left:*** *The temporal distribution shows a clear excess at zero, as expected for Compton scattered photons from the left to the right column of blocks.* ***Right:*** *The vertical position in the left vs. the right column of blocks of the same events, demonstrating that these are all 90^o scatters.*

(2.4) Looking at 'old' instrument data: GAP/COMPTEL

The GAP instrument was the first dedicated GRB polarimeter in space. Despite its small size, the instrument performed polarization measurements for 7 GRBs. It is important to note that only the results for 3 of these GRBs have been published to date as the other 4 GRB, although constraining in the parameter space, were not deemed precise enough by the instrument team. The analysis performed by the GAP team made use of the classical polarization analysis method described before. As GAP was designed as a dedicated GRB polarimeter and thus detailed instrument calibrations were performed, the GAP data is ideal for re-analysis using the method proposed here. Due to the inherently higher precision achievable with our method, we expect to produce measurement results with a higher precision for all 7 GRBs. The precision can be further improved by the fact that the majority of all these 7 GRBs were additionally measured by Fermi-GBM, allowing for a joint analysis and potentially detailed energy dependent polarization measurements. Initial discussions with the GAP team have taken place and they are positive towards the idea of re-analysis, particularly regarding the currently unpublished 4 GRBs. The GAP PI is member of our Advisory Board.

The COMPTEL instrument, flown between 1991-2000 on the Compton Gamma-Ray Observatory, was the first proper space detector based on Compton scattering, and thus was expected to provide unique measurements of the polarization in the 0.7-30 MeV band. Unfortunately, due to the combination of higher-than-expected gamma-ray background and poor (though best-possible at the time) instrument simulation and calibration, COMPTEL has significantly detected only a dozen sources plus two dozen GRBs, and polarization analyses always remained ambiguous. At MPE, we still maintain a workable database of the COMPTEL telescope, and recently have also dramatically improved upon the instrument simulation, allowing us to much better distinguish background from source photons (prior to Maximum-Entropy fitting). With our new analysis tools we are convinced that a new attempt of looking at the polarization properties of Crab and Cyg X-1 is very promising.

iv) Theoretical Modelling

We are developing a numerical tool that can calculate the observed polarization from a relativistically moving source with arbitrary geometries, velocity profiles and magnetic field configurations. Such a tool can be used to evaluate the polarization from a variety of astrophysical sources. It can be used to fit the probable magnetic field configuration and system parameters using the evolution in time of the observed degree of polarization and the electric vector position angle.

Presently, we can calculate the polarization from 2D surfaces propagating at relativistic velocities. The polarization can be calculated from arbitrary magnetic field configurations, spectral energy distribution (SED) of the emitting particles and velocity profiles. We can then fit the evolution in time of the DOP as well as the EVPA to observations of polarized radiation from GRB prompt and afterglow emission (see Fig. 12). The tool can work on both analytic input as well as simulations data files from relativistic magneto-hydrodynamic (MHD) simulations.

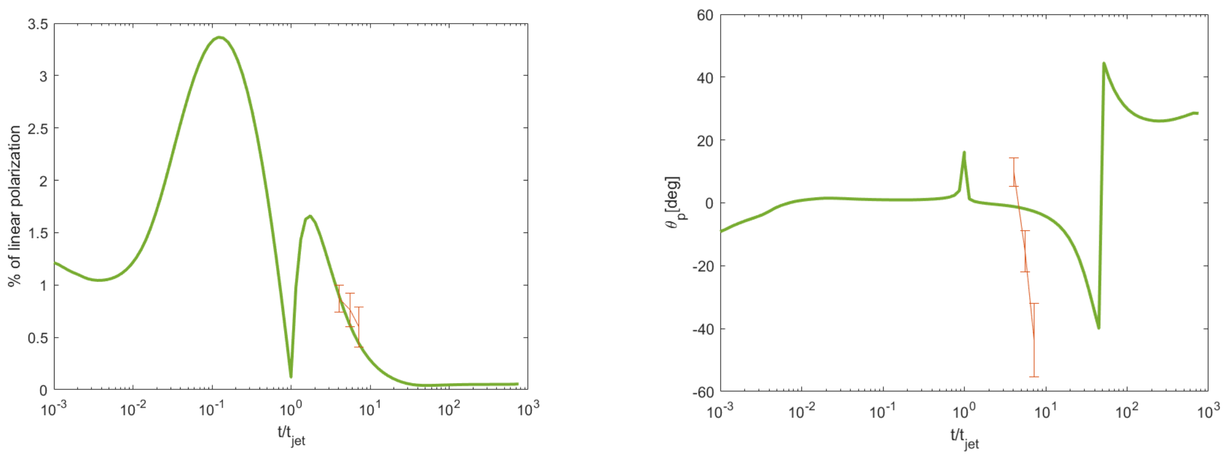


Figure 12: Present modelling status of the change of the degree of polarization (left) and polarization angle (right) over time for the specific application of the gamma-ray burst GRB 190114C.

In the second stage, we intend to generalize our tool to account for emission from 3D volumetric regions. If the source is moving with a relativistic velocity, the observed emission at each time interval arrives from distinct surfaces (surfaces if equal arrival time), the shape of which is dictated by the velocity distribution and by the geometry of the system. These surfaces need to be calculated for each system independently. The calculation will be done following a similar method that was used by us previously (Bromberg et al. 2018, MNRAS 475, 2971; Nakar et al. 2018, ApJ 867, 18). In these works we calculated the lightcurve based on MHD and HD simulations of relativistic GRB jets. Applying our tool on the simulation data will allow us to obtain the observed polarization as well. In order to account for line of sight effects through the 3D emitting region which may contribute to the polarizaiton such as synchrotron self-absorption or Compton scattering, we will implement a Monte-Carlo method that will calculate the radiation transfer effects on individual photons in the system. The Monte-Carlo module will be developed separately from the polarization tool and will be integrated into it. The development of both tools can help us better understand the polarization from a broader set of objects such as SGR giant flares, pulsar wind nebulae and extragalactic jets and more.

v) Attempt to gain new insight into sources

With (i) our new data analysis tools (proper statistics, multi-instrument fitting, improved data and response matrix formats), (ii) data handling and modelling tools (3ML, time-resolved, energy-resolved), and (iii) improved and new INTEGRAL calibration and data reduction tools, we will be in a privileged position to obtain polarization measurements which are much more accurate (due to the better base knowledge) and precise (due to proper propagation of uncertainties) than any measurements before. In addition, we will likely obtain time- and energy-dependent results per instrument, not being possible in the past. These new measurements will enable completely new physical questions to be asked. Together with our new theoretical modelling we will able to address these questions at a unprecedented level of physical depth. We anticipate that this will set the standard for future polarization measurements, and trigger completely new observational approaches to address the new questions we will pose. This may create also new theoretical challenges.

vi) Serving the community: add tools, data and theory to archive

Tools: The project aims to produce a fully functional framework which can be easily implemented for past, current and future instruments. Beyond POLAR-2, two specific examples of future instruments which can make use of the tools are the IXPE mission, foreseen for launch in 2021, and the Chinese-European eXTP mission which aims to launch in 2027. Although IXPE is likely to have an analysis framework developed by the collaboration itself by 2021, the tools developed by the POLCA project during the years that IXPE is active will allow for a direct comparison and should allow for more precise measurements. For eXTP, all the tools will be available and well tested before launch. As both, the Geneva and MPE groups are involved in the eXTP mission, and the PI of eXTP is heavily involved in the POLAR-2 mission, it is probable that the full eXTP analysis framework can be based on that developed during this project.

Data: The high-level data from all instruments discussed here, SPI, IBIS, POLAR and GAP, will be made available to the community together with the instrument response in the format such that it can be used by the general community and for joint fitting by future instruments. For example, data from the Crab pulsar will be available from all these instruments and can be used by the eXTP collaboration for performing energy dependent polarization fits spanning an energy range from keV to MeV.

Theory: The theoretical models developed here can be directly fitted to the data by any instrument using the tools developed in this project. It thereby becomes trivial for other instrument teams, once they have their data and instrument response in the right format, to fit to the different theoretical models produced here.

vii) Preparation for future missions

At the moment, no standard data analysis methods, analysis tools, or statistical procedures exist for high-energy polarimetry. As a result, every past mission with the capability to measure high-energy polarization has in some way reinvented the wheel. This has not only been very time-consuming for each collaboration, but has additionally lead to sub-optimal or simply wrong analyses being published. With the POLCA project we aim to provide a set of well-tested tools which can be easily used by any future polarimetry mission. Our goal is to provide a situation similar to that for spectrometer missions, which, prior to launch, are aware of which data format needs to be used, how to produce the instrument response and which tools are available for data analysis. As a result, the development time will be greatly reduced while the produced analysis results will be significantly more reliable.

A second product of the project, which is of use to future missions, are the measurement results. By providing polarization measurement results from a range of instruments for continuous sources such as the Crab, these sources can be used as calibration targets for future missions. Such calibration sources are currently not available for polarimetry missions, making instrument calibration more cumbersome as well as less reliable.

Finally, by developing theoretical models, future missions will be able to optimize the instrumentation to answer specific questions. For example, during the development phase the instrument design can be optimized in order for it to distinguish between different emission models using a minimal observation time.

viii) Optimization of the POLAR-2 mission

POLAR-2 is the follow-up of the successful POLAR mission which produced the largest set of constraining GRB polarization measurements to date. POLAR-2 will start taking data in 2024 as the largest and most sensitive gamma-ray polarimeter with GRB polarimetry as the primary science goal. The POLAR-2 mission greatly benefits from the heritage of the POLAR mission and in particular the lessons learned from the analysis of the POLAR data.

We aim to optimize the scientific potential of this mission in 2 separate ways. The first is by building a framework based on the analysis tools developed in this project for the future analysis of the POLAR-2 data. POLAR-2 is an optimum candidate for this not only due to the time of its launch but also as the analysis procedure described here is largely based on lessons learned from the POLAR mission. The aim is that as soon as data from POLAR-2 is downloaded to ground, analysis with the optimized open source tools can commence, forming the first future application of all the tools developed here. This not only ensures an efficient and transparent data analysis but also allows to advertise the work performed during the POLCA project.

Secondly, an important lesson learned from the POLAR project is the sensitivity of the polarization analysis on the spectral parameters of the observed source. In order to solve this issue the joint fitting of POLAR data with spectrometer data from Fermi-GBM was started which formed the basis of the future polarization tools we present here. Although the development of an optimized analysis procedure solves part of the problem, no spectral measurements were performed for the majority of the GRBs detected by POLAR. Large errors on polarization parameters are therefore induced by the lack of spectral data. A similar argument can be made for localization of the GRB. In order to overcome both problems, the MPE group has proposed to place a dedicated spectrometer on the POLAR-2 mission. This happened after the mission had been adopted by the Chinese Space Agency, and after funding granted by the Swiss Space Organization. Thanks to our heritage with spectrometer development for space missions (Fermi-GBM, INTEGRAL-SPI) such detectors can be developed at a low cost while greatly enhancing the scientific performance of the POLAR-2 mission. Thus, WP6 contains a task to develop such a spectrometer, and the corresponding budget is listed under “Other direct costs” (see details in sect. 3.4). Additionally, the access to dedicated spectral, location and polarization data from a single mission will allow us to test all the products developed during the POLCA project to its maximum effect within a year of the end of the funding period. Contributions to the POLAR-2 project will therefore fully ensure continued use of the applications developed here after the funding period ends.

ix) Gender dimension

The gender dimension in research and innovation is an essential aspect of research excellence, as it increases the societal relevance of the knowledge produced, as well as technologies and innovations. Addressing sex and/or gender aspects is an emerging and important dimension of research in many scientific and technological fields, representing a valuable source of innovation. Most obvious fields include "applied" sciences such as health, demographic change, future transport and mobility or robotics. Also in space there are a number of relevant areas, including female astronauts or the diversity of future inhabitants on Moon and Mars. In our field of basic research the gender dimension comes down to the question of emotional intelligence, creativity, and critical reflection.

We do believe that intellectual capacity, and cognitivity of hitherto unknown facts and relations are equally distributed between men and woman. Yet, women are typically considered to possess higher emotional intelligence and creativity. This is particularly important in collaborative work as the one we propose here. Diverse teams are known to be more effective. Collaboration in (or with) a diverse team will drive innovation. In this context, diversity encompasses quite a wide range of properties, such as gender, race, religion or social and cultural style and habits. Each of these properties leads to different viewpoints, forcing more discussion, and thus more collaborative communication. A short-hand version of this connection is the statement that "women promote collaboration" (Bear & Woolley 2011, Interdisc. Sci. Ret., Vol. 36, p. 146).

Another aspect in research is that innovation, when reached in a collaborative environment, creates equity (Misra et al. 2017, Soc. Sci. 6, p. 25) in the collaboration itself, but also in its broader environment by not promoting egos to grow. With more equity easing more collaboration, the circle closes. The consequence is that a team is scientifically strenghtend by having diverse viewpoints, and this in turn promotes future equity.

One particular application for our collaboration will be the cultural differences with respect to our collaborating partner country Israel. As described above, we consider this part of the diversity and thus beneficial for our collaborative communication style. We do will pay special attention to e.g. different opportunities and constraints in the mobility concerning mutual research visits. On more general terms, the collaboration will, of course, follow the EU strategies on gender equality as laid down in the H2020 program.

1.4 Ambition

The goal of our proposal is to enable the measurement of high-energy polarization which, we note, has been attempted in the past. Our present proposal has developed as a result of decades-long study of physical processes leading to polarized emission, activities to measure polarized emission, development of new analysis software, and engagement to push for new polarization instruments. Our ambition is to combine **novel concepts** and **ground-braking objectives** to obtain a **major advancement** in our understanding of polarization which exceeds the current state-of-the-art and these past attempts in three notable ways:

- we present a generic framework for all high-energy polarization analysis
- we provide usable, public models for the community to test their own theory and data
- our work and software are open source providing the community the ability to improve and scrutinize our approach.

Astrophysical polarization measurements are difficult: With present-day technology, a position of an astrophysical source can be measured to decent significance with a handful of photons. The measurement of the energy spectrum of an astrophysical source requires about 100 photons (per energy decade). In contrast, a polarization measurement requires at least about 1000 photons!

In detail, our ambition for new developments covers the following areas:

a. <u>Combined fitting:</u> Typically, high-energy instruments measure more than one photon property, i.e. time of arrival and spectrum, or sky position and spectrum. Yet, standard analysis techniques nearly exclusively fit models to one of these measured quantities at a time. Since several years, we have been **developing a toolkit** for the analysis of Fermi/GBM (Gamma-ray Burst Monitor) data to fit the spectrum and the sky position of a GRB at the same time (Burgess et al. 2018, MN 476, 1427; Berlato et al. 2019, ApJ 873, 60). While the whole process of GRB localization with Fermi/GBM and CGRO/BATSE (Burst and Transient spectrometer Experiment on the Compton Gamma-Ray Observatory) is based on the different spectral appearances in differently oriented detectors, the analysis has been split into two steps: first deriving a position under the assumption of a fixed spectral model, and then using that position to fit the spectrum (Pendleton et al. 1999, ApJ 512, 362). That is, the deficiency of the algorithm was known, but it took 30 years to be corrected. In a similar spirit we developed a fitting engine for a combined spectral and polarization analysis, applicable to the POLAR instrument. Combined fitting of multiple parameters as well as different instruments is the proper way.

b. <u>Rigorous statistical treatment:</u> Temporal or spectral re-binning of low-significance data points has long been the default approach. Yet, information is lost in this process. Dealing with unbinned data then implies the use of proper statistical treatment in the low-count regime. The conclusions reached with such approach can be dramatically different (Greiner et al. 2016, ApJ 827, L38). Another problematic area is the fact that statistical uncertainties are frequently only applied to the last step of an analysis, however, the systematics and unknowns of instrumental calibration can also induce uncertainties in an analysis, even if they are typically ignored. Lee et al. (2011, ApJ 731, 126) found that including a statistical approach to calibration improves the ability to recover the true parameters in an X-ray analysis. We will leverage this **cutting-edge approach** to the much more uncertain calibration regime of X-ray polarization. Our **unique, and innovative combination** of statistical analysis from the instrument to the observation will not only provide a **novel and robust framework** for polarization studies, but have a *major impact* beyond the current study as the approach can be adopted into areas outside our current focus.

c. Fitting physical spectral models: For decades, and still standard practice today, the spectra of synchrotron emission sources are fit with a power law, and physical interpretation is thereafter based on the best-fit slope of the power law. First demonstrated for a single GRB (Burgess et al. 2014, ApJ 784, 17), but recently also for a complete sample of Fermi/GBM-detected GRBs, fitting synchrotron spectra (incl. electron cooling) rather than power laws leads to a surprisingly different result: instead of 25% of all spectra violating the so-called "synchrotron death line" (in case of power law fitting), the synchrotron model fits 95% of all time-resolved spectra (Burgess et al. 2019, Nat Astron 3, 471). This approach needs to be extended to polarization models as well, and is the reason why our project incorporates a major theoretical study.

d. Physically appropriate data selection: Gamma-ray bursts are rapidly evolving events, with many measurable parameters (like energy spectrum) changing on timescales down to the measurement accuracy. Yet, standard polarization analysis often tried to maximize the "signal-to-noise" (S/N) ratio by analysing all events, integrated over the full GRB duration. For spectral analysis it is well known that time-integrated results have not much resemblance with time-resolved results. Time-resolved analysis, however, implies low-count regime, and thus requires proper statistical treatment (see above). Our re-analysis of one GRB of the POLAR sample (Zhang et al. 2019, Nat. Astron 3, 258) therefore incorporated two improvements: first, the inclusion of Fermi/GBM data and a combined fitting of the spectrum (GBM data) and polarization (POLAR data), and second, a time-resolved polarization analysis. For this, the data were divided into 9 time bins, roughly on the order of the minimum variability timescale, and the spectrum and the polarization angle and degree were allowed to vary between the time bins. We found a trend of growing polarization in time, reaching values of about 30% at the temporal peak of the emission. Even more interesting, we also observed that the polarization angle evolves with time throughout the emission (Burgess et al. 2019, A&A 627, 105). If this is a generic property of all GRBs, then in the time-integrated polarization analysis in the past, including that of INTEGRAL data (Götz et al. 2013, MNRAS 431, 3550, Laurent et al. 2016, 41th COSPAR Sci. Assembly, id. E1.15-18-16), the polarization signal was smeared out. Thus, our results of the POLAR analysis call for a **re-analysis of the INTEGRAL polarization measurements** in a time-resolved fashion.

e. Building theoretical understanding of the sources of polarized emission: The analytic polarization models presented above were made for a specific configuration of magnetic fields, electron energy distributions and assuming uniform radial velocity profile. There calculations are also limited for emission from two-dimensional optically thin surfaces and cannot be applied to more involved environments, which emits from 3D volumetric regions. Recently, we have constructed a numerical tool, based on the method presented in Nava et al. (2016, MNRAS 455, 1594) that can calculate the observed polarization from arbitrary jet structures, magnetic field configurations and electrons distributions. It can also follow the evolution in time of the polarization including the rotation of the EVPA. Currently our tool is capable of calculating polarization from 2D, optically thin surfaces. It can be used for fitting the observed polarization in GRBs prompt and AG emissions with a probable magnetic field configurations on the shock plain. We are now in the process of generalizing the calculation to
3D, volumetric regions. This will allow us to use the model to analyze emission from a variety of sources which emit synchrotron radiation from optically thin, 3D regions, like soft-gamma repeaters, pulsar wind nebulae and extra-galactic jets (see next sect.).

Our proposed task is to eliminate the burdens of the past, develop tools for the future and apply these advances to past data providing a tested framework for future missions. We will leverage the proven heritage of high-energy spectroscopy to develop open, accessible tools, databases, and methodology enabling any astronomer to analyze sources with their chosen physical models, extending the success of the last 40 years in X-ray spectroscopy to a virtually untapped innovation potential.

2. Impact

2.1 Expected impacts

POLCA will push our understanding of the physical processes in high-energy astrophysical sources. The project will add value to the data of ESA's cornerstone mission INTEGRAL by providing new tools and methods for the analysis and interpretation of the data. POLCA will also open up the access to space data to a wider community by making it easier to incorporate polarization data into their analyses.

The POLCA research and developments will result in a significant number of publications, new tools, enhanced data products, and model deliveries for calibration and interpretation of the data from high-energy missions, past, operating as well as future.

In fact, some of the most important signatures of physical processes is locked away in the *polarization* of these photons. While there exist instruments designed to measure polarization, both still active and retired, the extraction of these signals from the data have been hampered by multitude of issues including the difficultly in measuring high-energy polarization, the unavoidable lack of a large number of photons at high-energy, lack of open access to the data and analysis tools, as well as relatively immature analysis techniques. Thus, polarization is the last frontier in high-energy electromagnetic science as well as a modern challenge on many fronts.

The following sub-sections detail some of our major expected impacts:

a) Impact on science

Our proposed developments within the POLCA research project will result in a **significant number of scientific publications** on a variety of source types. Below we describe those, where we anticipate largest impact.

Polarization in Gamma-Ray Bursts: Despite 40 years of measuring energy spectra and light curves of GRBs, the origin of the burst emission and its fundamental physical emission process is a matter of heated debate. The two main contenders are photospheric emission (e.g. Ryde 2004, ApJ 614, 827) and synchrotron emission (Meszaros & Rees 1993, ApJ 418, L59; Burgess et al. 2019, Nat. Astron. 3, **471**). Both models predict polarized γ-ray emission, but with different time- and energy-dependence (e.g. Beloborodov & Meszaros 2017, SSRv 207, 87). This might allow us to distinguish between these two prime models (Toma et al. 2009, ApJ 698, 1042), which provides one of the main scientific drivers of this project.

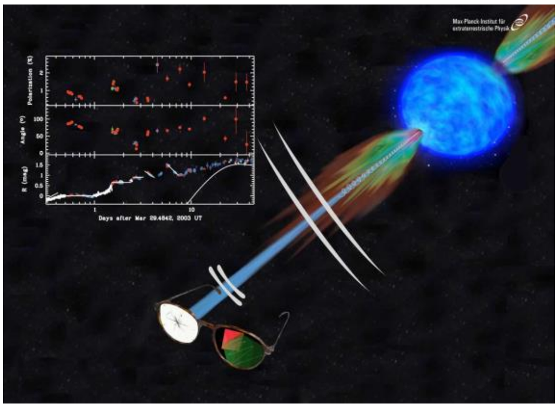


Figure 13: Scetch of polarized radiation being produced in the jet of a GRB. The inset shows how polarization degree and angle of the afterglow emission change over 10 days.

Polarization in Soft Gamma Repeaters (SGR): SGRs are neutron stars with particularly strong magnetic field, up to 10^{14}-10^{15} Gauss, which show occasional periods of outbursts of high-energy emission similar to GRBs. Many models exist for the origin of this emission, and correspondingly a variety of possibilities for polarized emission, among others (i) resonant Comptonization of thermal photons by charges moving in a twisted magnetosphere, (ii) scattered radiation from a trapped fireball in a closed-field-line region, (iii) resonant cyclotron upscattering of soft thermal photons from the stellar surface by relativistic electrons in the magnetosphere, (iv) magnetic photon-splitting (50-500 keV) in the presence of a strongly magnetized electron-positron plasma. We expect that with our new re-analysis of INTEGRAL data we will be able to at least constrain the range of models and parameters, if not pinpointing to one particular model.

Polarization in Pulsars: Pulsar γ-radiation is produced by extremely relativistic ($\gamma \sim 10^6$ - 10^7) electrons (and positrons) propagating along the curved field lines close to the speed-of-light cylinder, which marks the outer extent of the co-rotating magnetosphere. Photon-electron cascades are generated by the interplay of electron curvature radiation, inverse Compton scattering (at GeV energies), synchrotron processes (MeV range) and pair creation from photon-B-field interactions. Since the particle flow is aligned with the magnetic field, the emitted γ-rays delineate the field geometry. Furthermore, one expects a significant polarization of the emitted radiation, because the geometry is very anisotropic and the relevant emission processes are *per se* highly polarized from the predefined magnetic-field direction. Depending on the specific model for the generation of γ-rays, the prediction of the polarization is different. A common feature, however, is the change of polarization degree and angle with both, the magnetic field inclination relative to the rotation axis, and the observer viewing angle. Thus, phase-resolved polarization measurements are a must (Dyks et al. 2004, ApJ 606, 1125). The most prominent γ-ray pulsar (with a surrounding pulsar wind nebula, PWN) is the Crab, for which time-dependent polarization results have been recently published by the ASTROSAT team (Vadawale et al. 2018, Nat. Astron. 2, 50), but are widely criticized for both, wrong methodology and overestimated significance. Thus, a thorough analysis of complementary INTEGRAL data will settle this issue.

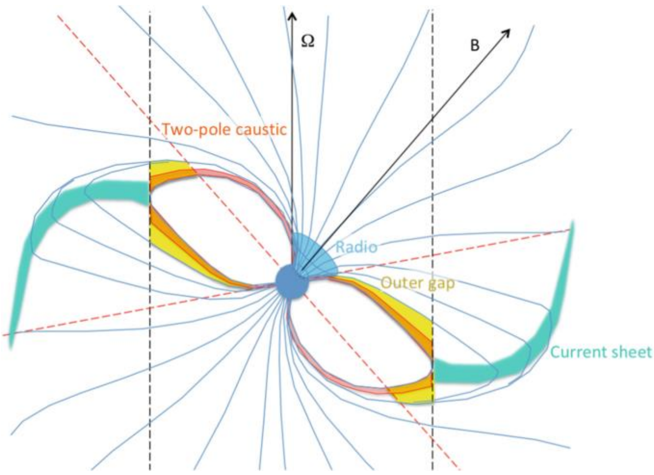


Figure 14: Sketch of the magnetic field configuration in a pulsar [From Harding 2019, in "Astronomical Polarisation from the Infrared to Gamma Rays", eds. R. Mignani et al, ASSL 460, p. 277]

Polarization in Galactic jet sources (incl. microquasars) and Blazars: The geometry and origin of the X-/gamma-emission in these two classes of jet sources is heavily debated. In microquasars, a comptonized corona is usually considered as the source of high-energy emission, but a report on 75%±32% polarization in the hard state has spurred the interpretation of synchrotron self-Compton emission from the jets (Rodriguez et al. 2015, ApJ 807, 17). Our improved analysis should clarify whether this 2σ result can be improved towards a significant detection, or should be dropped as insignificant. In blazars, leptonic models do predict polarization due to the prevalence of synchrotron radiation from the jet, but hadronic (unpolarised) models are popular, though a smoking gun for accelerated protons is still missing. Polarization results of Cyg X-1 have been reported with both INTEGRAL instruments (Jourdain et al. 2012, ApJ 761, 27; Rodriguez et al. 2015, ApJ 807, 17). With our broad approach of three different analyses (incl. the new ISGRI-only approach), Cyg X-1 is a particularly important source to also demonstrate the internal consistency of our three methods.

Polarization of disk-dominated AGN: The standard model for the origin of the high-energy emission is Compton up-scattering of the thermal, soft accretion disk photons by a relativistic plasma located as a corona around the central disk. Polarization of these Compton-scattered photons, since views away from the symmetry axis, will allow us to measure the unknown origin and geometry (via the polarization angle) of this coronal source (Krawczynski et al. 2012, ApJ 744, 30): optically thin accretion disks have predicted polarization levels of order 30-60%, while optically thick disks show only low levels (10%). Our new analysis approach has the promise that polarization measurements can finally, and possibly decisively, contribute to this debate.

b) Relation to other EU-funded projects

The measurement of polarization provides an impact far beyond its face value due to the fact that polarization information uniquely allows for an observer to infer properties about the physical and magnetic geometry of the emitting object. There then exist secondary multipliers of impact on other EU observatories, i.e. POLCA will **add value to existing activities on European level**. For example, the ability to measure high-energy polarization from blazars via archival data from EU-member-states- and ESA-funded instruments such as INTEGRAL improves our understanding of these objects jet geometry and magnetic field strengths. The EU-funded KM3NeT neutrino observatory can use this complimentary information to build more precise models for the expected neutrino emission from blazars. As neutrino detection is dominated by local backgrounds, having the information from polarization enables the use of highly predictive models which allows for signals to be identified in the backgrounds. Thus, the impact of our proposed program extends far beyond the project, and can **enhance and broaden research partnerships** between space and ground-based research.

In the same light, measurement of polarization from GRB jets helps to identify the extent of their jet opening angles. With the recent connection of short GRBs to neutron star mergers (detected via gravitational waves) and the associated infrared/optical kilonova, understanding the opening angle of these jets is a direct measurement of their population detectability. There are many EU/ERC/Marie-Curie funded programs (e.g. TEDE, TReX, JetNS, PHAROS, GWVerse, BinGraSp, MAGNESIA) focused on searching for kilonovae (either via ESO's telescopes or those national facilities for which access is granted via OPTICON) or understanding the related physics of GRBs or gravitational waves. Thus, using polarization measurements to understand the physical geometry of GRB jets **supplements the high-impact science of other EU observatories and projects** directly.

c) Impact on data format

Standardization of the polarization data format has the impact of providing a uniform method for the community to access, model, and analyze data. By eliminating the obstacle of having to discover the intricacies of varying data formats, how to interpret them, which tools are readily available to read them, researchers can focus on the important aspect of the analysis: science.

A secondary impact is that our focus on formatting and providing standardized data can inspire other fields to implement similar approaches, further enhancing data from other ESA-related missions. Indeed, our inspiration is a secondary of the initiatives in high-energy astronomy to have common data formats – see https://gamma-astro-data-formats.readthedocs.io.

d) Impact on software tools

The last ~40 years have seen an unprecedented gain in knowledge due to the instrumentation, methodology, and the availability of high-energy spectroscopic data analysis tools such as XSPEC. Our understanding of relativistic and nuclear physical processes from these advancements has been made even deeper with the new multi-wavelength era by extending measurements of astrophysical phenomena across the electromagnetic spectrum. However, we have yet to extract all the information carried across the Universe from the photon messengers. Now we bring that frontier to science of high-energy polarization by establishing an analysis environment for polarization, similar to what XSPEC constitutes for X-ray spectroscopy.

e) ESA's INTEGRAL archive

We anticipate three immediate impacts: First, because of our new (re-)calibration software, the presently available standard tools for INTEGRAL IBIS and SPI should get consistent with each other. Secondly, we plan to place our **high-level data products** as well as the **analysis tools and methods developed for the advanced processing of the data** into the INTEGRAL archive, such that the community has direct and easy-to-find access for verification, further developments, or cross-correlation with other data. Thirdly, with the advent of polarization analysis tools, the **INTEGRAL archive** will develop much higher attraction to the community, with the synergetic side effect of motivating scientists to use all types of INTEGRAL data for their multi-wavelength studies.

f) Impact on theoretical modelling

Theoretical modelling of polarization is currently restricted to explaining general polarization signals. Applying our rigorous analysis and the numerical tool on the wealth of obtained data from INTEGRAL (and other missions) can provide better constraints on the global morphology of the system and that of the magnetic field. This will allow us to rule out some of the physical models that exist for the studied systems, or to extend certain models which in turn requires additional micro- or macro-physical parameter input (e.g. jet-precession, geometry). Such constraints are uniquely possible only with polarization data, but not with spectroscopy as obtained in the past.

g) Impact on future mission

The POLCA project aims to bring the field of high-energy polarimetry to a more mature level where standard analysis tools, standardized data formats and instrument responses exist as well as in-orbit calibration sources. POLCA aims at a concept of universal polarization response that includes the energy dispersion as well as the scattering angle dispersion, allowing astronomers to make inter-instrument calibration and joint analysis possible. The project will vastly reduce the time required for future missions to develop their analysis pipeline and will allow for faster and more accurate measurements to be produced. By additionally providing a range of existing measurements as well as a development of theoretical models, the design of future instruments can be optimized better to further increase their scientific potential. Approved space missions to which this applies are IXPE, POLAR-2, and eXTP.

h) Open science

Open science initiatives increase access to disenfranchised communities, insure a robust scientific debate, and lead to more innovative outcomes due to transparency of analysis and data. Our project not only embeds itself in open science, but explicitly encourages its growth in the following several ways:

- opening the access to low-level data products related to polarization in such a way that a wide community can use both archival and future data products to perform both high and low level analysis
- opening access to detailed physical modeling of polarization signals so that the entire community can test said models and any of their derivatives against data from any instrument.

- providing an entirely open, community-driven software/analysis framework to unite the first two initiatives together.

The entire focus of the project deploys a modular approach to open science so that the community can take elements and build their own innovative analysis projects that can extend far beyond what we initially envision. These types of secondary products can only be achieved in an open science environment as transparency allows for unfamiliar or inexperienced members of the community to comprehend tools and models at a deeper level, thus, inspiring further creativity. Tools and/or software presented in a blackbox to communities tend to inspire trust and lack of discussion in scientific communities which can shut out newer members who may question the use of such tools. Therefore, we have designed our project to be a beacon of open science.

i) Impact beyond astronomy

Polarization has already several applications in daily life, from polarization glasses to watch 3D movies to special glass to reduce the glare of headlights of cars. X-ray polarization is less common, since we have no X-ray vision. Yet, over the last decade it has been rapidly developing to a highly effective method in several fields, most notably in so-called magnetic microscopy. This uses polarized X-rays in e.g. solid state physics to design and investigate light-weight magnetic materials. Another example is the study of biological systems since magnetic switching can achieved at femto-second timescales, allowing the study of the dynamics of any spin systems at timescales commensurate with reaction times. Our sub-task of developing proper statistical methods for the analysis of polarization measurements will be directly applicable to such lab-experiments.

Our main concern in terms of achieving the expected impact is the **acceptance** of our results by the INTEGRAL instrument teams (IBIS and SPI). Whenever new methods are introduced in what is considered an “established” field, scepticism is large. This is a well-known feature and reflects the cautious behaviour of scientists before accepting something new. Some of our team members have experienced this with the 3ML package which originally was developed without (Fermi) team consensus, and was started to be used heavily only after other teams have found it useful. We are prepared to tackle this acceptance problem, and have taken several measures to mitigate this, as described in more detail below under sect. 3.2.(b) Innovation Management.

2.2 Measures to maximise impact

(a) Dissemination and exploitation of results

i) Plan for dissemination and exploitation

In order to meet the needs of the potential users of our data and tools (primarily POLAR-2 and eXTP) as well as the stakeholders of the raw data (ESA, Chinese Space Agency, JAXA, national European space agencies), we propose the following plan for dissemination and exploitation:

a) Dissemination to the scientific community

The main communication channels within the scientific and high-energy astrophysics (HEA) community are conferences and publications. The POLCA team will be regularly attending the relevant national, European and worldwide scientific conferences for the HEA community (annual meetings of the Astronomische Gesellschaft, annual INTEGRAL meetings, international topical meetings on polarization or specific source classes like GRBs, jet sources etc.) and presenting the status of research and the obtained results. This will not only publicise our results, but also advertise the science funding through the H2020 program, as well as the fruitful link between the EU science program and ESA activities. All presentations will be made available also on the public POLCA web page.

b) Enhancing the innovation capacity

Innovation beyond our specific research project will be possible by reaching out to parts of the astrophysics community outside the high-energy domain. For instance, optical polarization measurements of GRB afterglows is a well established sub-field, and synergies can be expected by comparing the polarization properties from the prompt via the afterglow to the supernova phase of a GRB. Similarly, polarization measurements of blazars are available, providing the opportunity for a first comparison with our gamma-ray polarization measurements and consequently tests of models. Such multi-wavelength synergies will allow us to integrate new knowledge into the POLAR project.

c) Data and knowledge management

Raw data and auxiliary instrument data are publicly available, except for the most recent 12 months after observation. As all our work is meant to foster science and deepening the understanding of the physical processes in the astrophysical sources, we plan to make all results, high-level products and tools publicly available immediately with the publication in the scientific literature (see next item). Thus, there is nothing like “knowledge protection”. Quite the opposite is true: we want the astrophysical community to adopt (and potentially further develop) our tools.

d) Open access

We will be happy to participate in the Open Research Data Pilot program under H2020. A large part of our impact does hinge on making our software analysis tools publicly available, and thus we will plan for a Data Management Plan as an early deliverable. As to open-access publications, we are all for it, but we actually do not need much funding for this, because (i) the Max-Planck Society has a special agreement with EDP Sciences (which publishes our default journal “Astronomy & Astrophysics”) which covers all Gold open access costs from Max-Planck authors, (ii) the journal "Astronomy & Astrophysics" publishes articles in the sections "Astronomical instrumentation", "Catalogs and data" and "Numerical methods and codes" in free access at no cost to authors. Since this covers 90% of our anticipated publication costs for free access, we only add costs for two theoretical papers in our budget below.

e) Freely available software

Besides the results and the data, also the software tools developed within the POLCA project will be made publicly available. We foresee three channels: (i) within the ESA/INTEGRAL DataLab, (ii) the widely used github repository, and (iii) our POLCA project Web-page.

The dissemination of software products and their source has been revolutionized by public repository hosts such as Github (https://github.com) which allow the entire scientific community to openly share, collaborate, and extend software. Our team has extensive experience with public dissemination of software products and their source as demonstrated with 3ML (https://github.com/threeML), public hosting of code developed at our institute (https://github.com/mpe-heg), and our own personal repositories (e.g. https://github.com/grburgess). Thus, we have the experience required to distribute, advertise, and maintain our software products (an essential component/result of this project) to the community at large. As a research organization, we have access to the complete free storage of software via GitHub and thus incur no direct costs for this public availability. All code will be tested upon public release via freely available continuous integration servers such as TravisCI (https://travis-ci.org). Additionally, to support the initiative of open-source code, we will appropriately license all of our software products to enable future users, researchers, and developers to build upon our results, thus multiplying the impact of our work.

f) Data curation and preservation

The raw data which we plan to re-analyze are archived at the ISDC (INTEGRAL Science Data Center) in Geneva as well as within ESA/ESOC (European Space Operations Centre) in Spain. We plan to add our high-level data as well as the necessary auxiliary data (simulations, response matrices) to this database. ESA has started planning for both, an extended science archive, as well as a new data query form, commonly called DataLab. If this project proposal is accepted, we will immediately contact ESA in order to support the definition of these new facilities, in order to make sure that polarization parameters can be ingested as well. We anticipate that after the end of this project, ESA will take care of preserving and curating our results and tools, as part of the overall INTEGRAL archive. Also, since it will be part of the larger INTEGRAL catalogue/data access, there will be little additional costs, which we anticipate ESA to cover. Direct contact to the INTEGRAL science project is guaranteed through its Project Scientist being member of our Advisory Board.

g) Looking ahead

There is little doubt that there will be a future gamma-ray space mission by ESA or NASA JAXA or CSA, to name a few. The focus of the recent and present proposals for such missions is on the multi-messenger (gravitational wave counterparts) aspect. Our results will certainly widen the view to include polarization, given its immense promise to learn the underlying physics of the observed astrophysical phenomena. Thus, POLCA results will likely shape the design and construction of future generation gamma-ray instruments.

ii) Workshop organisation

Apart from just participating in suitable conferences, we plan to foster more focused discussions on polarization aspects in high-energy sources by organizing topical workshops. Presently, we plan for two smaller workshops at 2 and 3 years into the POLCA project, and one larger one at the end to advertise our results.

iii) Training/Education

Training of students and young scientists is considered a very important way of motivating the younger generation for science, and to contribute to the education of junior scientific staff. Several team members (in fact at least one per participant) also have teaching obligations at connected universities, and thus the results from the POLCA project will go directly to young students, informing them about the up-to-date research topics.

Another aspect of training, which we have good experience with, are summer schools. Members of the team have been acting as tutors in some European summer schools. A rather famous one, dedicated exclusively to space, is the annual school in Alpbach, for which MPE is one of the organizers. We plan to present our results there as tutors, and thus advertise the H2020 EU science programs.

(b) Communication activities

We plan several different communication measures, each tailored at a specific audience:

1) Scientific publications: these are directed to the (high-energy) astrophysics community and shall describe the main scientific results. This will include separate publications on the analysis methodology, the developed software, as well as on separate source types (foremost GRBs and the Crab).
2) Conferences/Workshops: we plan the organisation of one or two major workshops for the (high-energy) polarization community to a) show work in progress, b) get more (free) input, c) spread our knowledge and make polarization measurements valuable and popular
3) Internet outreach: we plan a dedicated homepage for introducing the team, describing the (long-term) goals, and providing frequent updates on major milestones.
4) We intend to also use social media (twitter, facebook, Instagram) to popularize our research topic, and reach-out to polarization aficionados in other wavelength domains as well as data analysis and/or statistics groups.
5) Some senior members of our group have rather tight connections to science magazines like the “CERN Courier” (40.000 subscribers around the world) and news papers, incl. nationwide “Süddeutsche Zeitung” and “Spiegel” in Germany, or “Neue Züricher Zeitung” and “Schweizer Sonntagsblatt” in Switzerland. As appropriate, we will publicize our project results through these media.
6) At MPE and TAU a “Day of the open house” is organized every second year, attracting about 3500-5000 people per event. We will use these events as an extraordinary opportunity to inform the public about our results, and use astronomy as a means of motivating young people for a career in physics.
7) Similarly, we have the ESO Supernova Planetarium and Visitor Centre across the street of MPE, with rather direct access to the organizers, as part of the MPE team has been involved in creating the first exhibition.

8) Since a few years, at MPE and TAU (and also UNIGE) yearly “Girls days” are organized. Again, we will actively participate in these events with our project results, and help planting interest in sciences at an early age to fight stereotypes of “male” professions in society.
9) In all three cities (Munich, Geneva, Tel Aviv) yearly “The long Night of Science” events are organized where the science institutions expose their latest results to the public. It will be rather easy for us to participate and promote our H2020-funded project.
10) Apart from these regular events for the public, MPE, UNIGE and TAU (at their Wise observatory) are offering special guided tours through the institute. This is frequently used by schools and for annual work outings of larger companies, organized at their requests. We will provide one “station” for these 2-3 hrs tours.
11) We plan to continue our past engagement with the general public through public talks and contributions in existing event series:
    a. “Modern Physics” is a monthly series held in Munich, organized in collaboration of the two main Munich universities, which attracts of order 100-150 people at its evening lectures.
    b. “Café & Cosmos” is a series of evening discussions of scientists with the public, organized monthly in Munich by the local research institutes, incl. MPE. The format is distinctly different from a lecture: instead, a scientist is introducing a topic of modern research, and then answers questions of the public which takes the majority of the time.
    c. In the framework of collaboration of the Munich/Garching Campus of astrophysical institutes and the Excellence Cluster with the two Munich universities there is an annual “Girls do technology” summer university. We plan to participate in at least one of these summer courses, as this is a particularly effective way of early on fighting the imbalance in male vs. female students in the MINT area.
    d. “Astronomy-on-tap” is a series of public presentations about astronomy given at a bar in downtown Munich and Tel Aviv. The events take place roughly 2-3 times per semester, and are free and open to the public. These are not typical science lectures. The talks are short, accessible and engaging. Questions are encouraged through prizes that are handed out and by having astronomers among the crowd ready to join the conversation. Together with the relaxed, informal setting, this form of science outreach attracts a crowd of 150-250 people of all ages per event. Astronomy on Tap Tel Aviv is run by a TAU faculty member, who initiated it in mid-2019. Students and faculty members at TAU help run the events voluntarily, but expenses are incurred for equipment, prizes and minor speaker expenses. The Munich series just started in January 2020, with one of the two inauguration presentations given by a member of our project group.
    e. The Tel-Aviv University Astronomy Club (AstroClub for short) is a public outreach organization, voluntarily operated by graduate students of the Department of Astrophysics, Tel-Aviv University. AstroClub members aim to provide the general public with opportunities to learn about astronomy, thus making physics and science, in general, more accessible. The club's activities include monthly lectures in contemporary issues in astrophysics, guided stargazing, “open house” events at the Wise observatory, and special educational activities for youth. All activities are open to the general public, free of charge. No prior scientific knowledge is required. The club is operated with the kind support of the Raymond and Beverly Sackler Faculty of Exact Sciences, the School of Physics and Astronomy, and the Florence and George Wise Observatory of Tel-Aviv University.

3. Implementation

3.1 Work plan — Work packages, deliverables

We structure our work plan into 8 work packages (WPs). One WP will be solely dedicated to all data and software aspects, which are not instrument-specific (WP1), including data and response format, 3ML, Virtual Observatory interface, and the newly-to-develop energy-resolved polarization. Then we have two WPs with instrument-specific developments, one each for IBIS (WP2) and SPI (WP3), including calibrations, response generation/simulation, and the plugins for 3ML. Next, there is one WP to use the tools for re-analysis of all the INTEGRAL data (WP 4). WP5 covers the theoretical modelling of polarization in jet sources. Finally, a separate WP is devoted to applications beyond INTEGRAL, i.e. looking at the data of the previous COMPTEL mission, and looking ahead to our approved POLAR-2 mission, including a test-setup development for its new polarimeter. Two WPs will cover the management and the outreach/dissemination aspects, so in summary, our proposed structure looks as follows:

0. Management
1. Software Development
2. Polarization with the INTEGRAL/IBIS instrument
3. Polarization with the INTEGRAL/SPI instrument
4. Archival Analysis of published sources
5. Modelling
6. Application
7. Outreach and Dissemination

Full details including the various sub-packages are given in the 8 pages of Tab. 3.1b. A graphical presentation of these WPs and their inter-relation is given in the following figure.

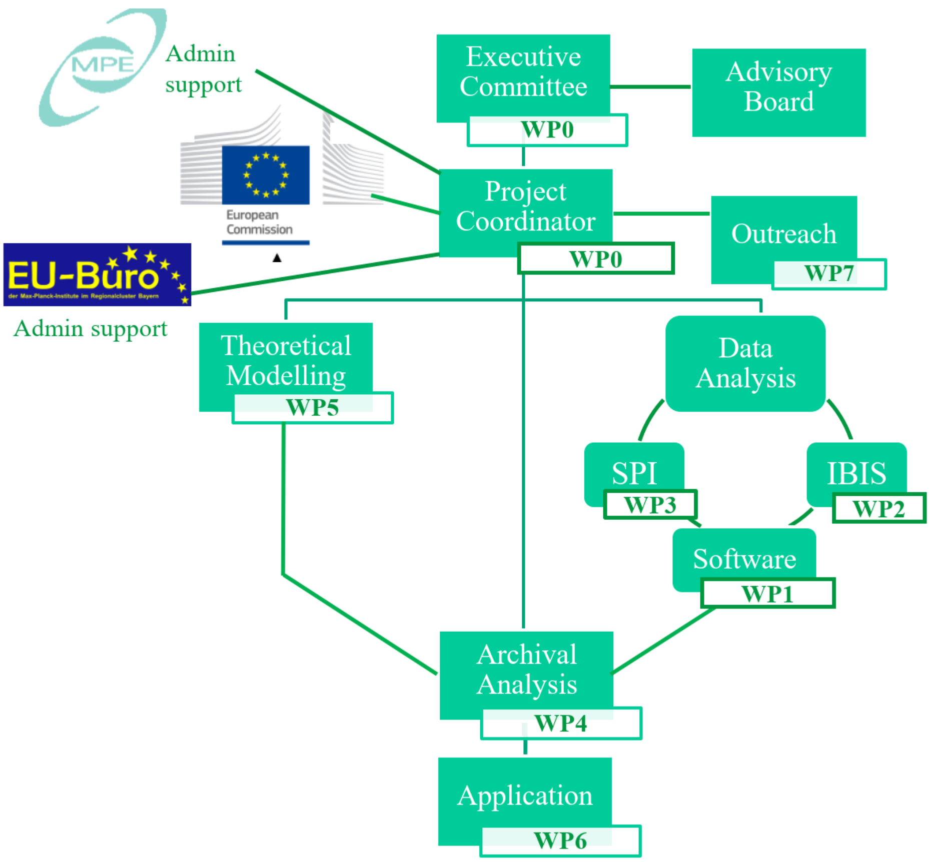


Figure 15: General structure of the work plan and inter-relation of the various work packages.

The timing of the different WPs is rather simple: WP1 should be the first priority in order to establish the tools, and WP2 and WP3 can thereafter be done in parallel (consistent with different groups being responsible for the two different detectors). The theoretical modelling will be ongoing all the time, with little influence on the other WPs until the last year. The detailed account of the allocated work load for each sub-WP and the corresponding assignment to one of the three participating groups including the distinction between PhD and post-doc assignment based on the complexity of the work is given in the table below. A Gantt chart showing the time flow of the WPs including all the separate sub-WPs is given in the figure on the next page.

Detailed assignment of work-packages to personnel (units: person-months).

Work Package	**MPE**			**UNIGE**		**TAU**	
	Managem.	PD (42)	PhD (42)	PD (42)	PhD (48)	PD (48)	PhD (48)
WP0	0[1]						
WP1.1		2		2			
WP1.2		2		2			
WP1.3				2			
WP1.4		2					
WP1.5		2					
WP1.6		1	2	1	1		
WP1.7		1		1			
WP2.1				5	8		
WP2.2				5	7		
WP2.3		2					
WP2.4				1	10		
WP2.5				15	15		
WP3.1		8	10	4			
WP3.2		7	10				
WP3.3		2					
WP3.4		7	13				
WP4.1		1		1		1	
WP4.2		1	2				
WP4.3					2		
WP4.4					2		
WP4.5			2			1	
WP5.1		1		1		32	
WP5.2							32
WP5.3						10	10
WP5.4						3	6
WP6.1		1	3				
WP6.2				1	3		
WP6.3		1					
WP7.1				1			
WP7.2						1	
WP7.3		1					

The most challenging tasks are (1) the development of the polarization response for IBIS incl. the development of the new ISGRI-only method, (2) the development of the polarization response for SPI, and (3) the design and physical implementation of the new radiation code. Each of these tasks requires an experienced post-doctoral researcher. The assignment of the theory post-doc to TAU is

[1] See the note below table 3.1a

obvious; for the two polarization responses we have split the responsibility between MPE (for SPI) and UNIGE (for IBIS). Most of the other tasks can be handled by clever PhD students (under supervision of the institutes senior staff and working closely with the post-doctoral researchers), and again we split the tasks (though this happens quite naturally) such that one PhD student each goes to one of the three participating nodes. The detailed distribution of the various tasks to the 6 individual researchers is presented in the table above.

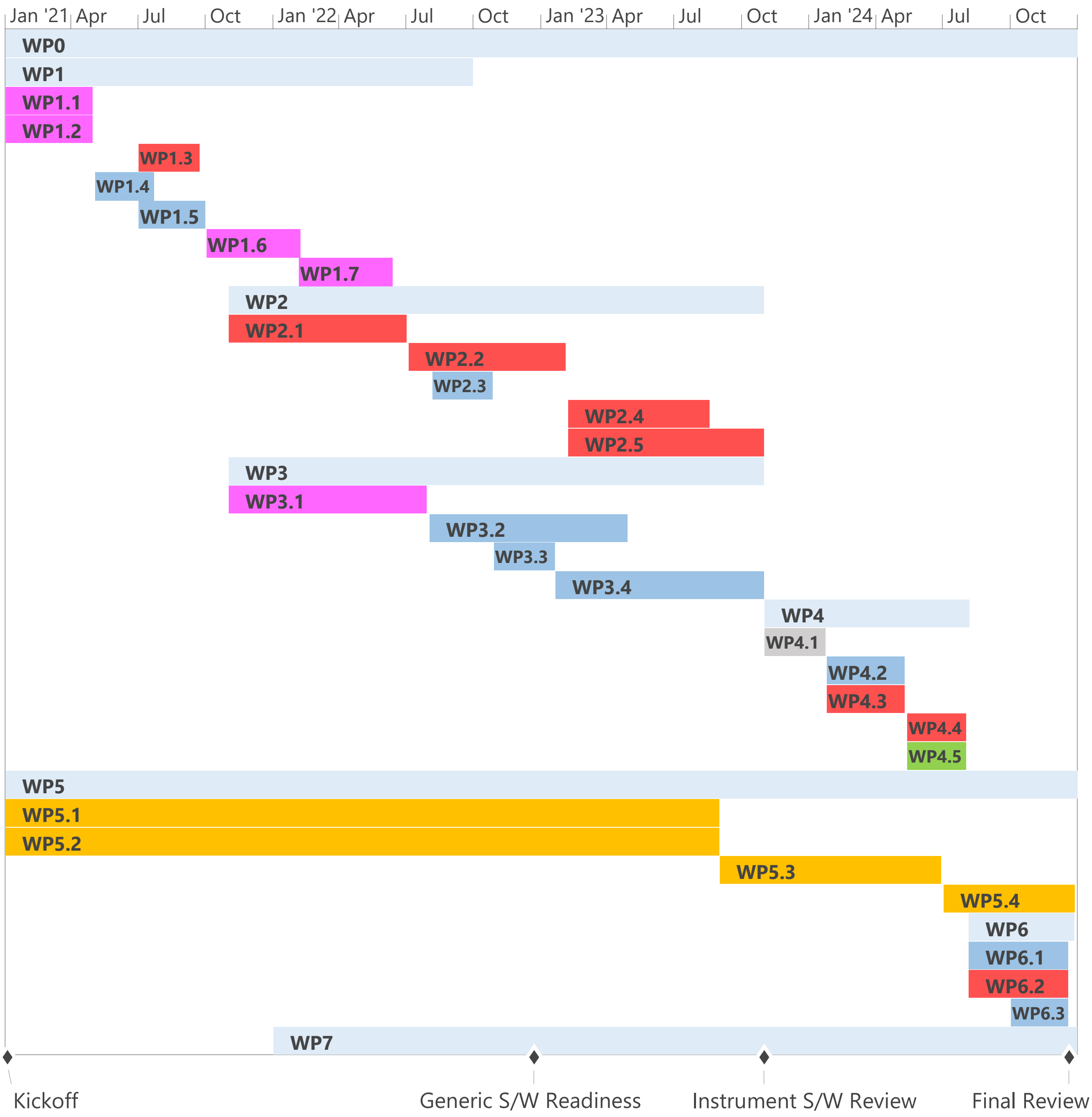


Figure 16: Gantt chart of the timing of the work packages. The main work packages W0-W7are shown in light blue. For the sub-WPs the contribution of the 3 nodes is coded, with the base colors blue (MPE), red (UNIGE) and yellow (TAU) showing sub-WPs to be executed by single nodes, and the corresponding additive color for collaborative sub-WPs (pink for MPE+UNIGE, green for MPE+TAU, and gray for MPE+UNIGE+TAU. Since each node plans to fund 1 post-doc and 1 PhD student, the length of the bars does not reflect the exact number of man-months, but rather the duration over which the work should be executed (most obviously for WP0 and WP7, where a few man-months are distributed over the full duration of the project).

3.2 Management structure, milestones and procedures

(a) Organisational structure

We anticipate that in addition to the six scientists funded through this H2020 program, there will be another 8-10 scientists involved in the various aspects of this activity. This includes technical staff for software development or executing simulations, supervisors of the PhD students, but also senior scientists for topics like connecting to ESA-internal infrastructure development (data format, data access, data storage), or links to other future (IXPE) or past (COMPTEL) instrumentation. In order to facilitate a quick decision process, foster tight connection to ESA's INTEGRAL project management team, and to allow for efficient management, we take the following measures:

1. **Project Coordinator:** the project coordinator (PC) is based at the coordinator institute (MPE) and is responsible for the organization of the administrative and scientific activities of the overall project. He will act as point of contact between the consortium and the European Commission and will ensure an efficient communication and dissemination of information between all parties. Moreover, the PC will monitor the development of the project, the time schedule, the quality of the work and of the documentation produced by each project unit and take actions to recover from eventual deviations from the planned schedule.
2. **Executive Committee:** we have agreed to form an Executive Committee (EC), which will consist of one representative of each of the three participating nodes. The EC will discuss and decide upon the most relevant and urgent project directives. Considering that each participant is based in a single physical place, critical issues can be efficiently discussed within each participating team before the final discussion restricted to the SEB (e.g. in a teleconference). It is expected that decisions will be taken by a general consensus; otherwise, decisions will be based on a majority vote with the PC having a casting vote.
3. **Advisory Board:** We have also opted to assign an Advisory Board for our activity, comprising the following members:

Name	Function	Benefit for this action
Dr. Erik Kuulkers (ESA)	INTEGRAL Project Scientist	Support in INTEGRAL and science related questions; coordination of software compatibility; Curation of data and products beyond this activity
Prof. Nicolas Produit (ISDC)*	Co-PI of POLAR-1 INTEGRAL IBIS Calibration Team	Detailed knowledge of INTEGRAL-IBIS instrument, as well as of needs for the future Swiss-German-Chinese POLAR-2 mission
Prof. Daisuke Yonetoku (Kanazawa University, Japan)	Principal Investigator of GAP	Specialized knowledge of instrumental issues of a Compton Polarimeter

*ISDC = INTEGRAL Science Data Center

The over-arching goal of having this Advisory Board is to ensure that the proposed polarization analysis is done with the broadest support of the high-energy astrophysics community, and to coordinate with efforts at ESA for a future data archive structure, called DataLab. We plan to make our analysis as well as the software easily available for future use, and an ESA-developed structure is the most appropriate for INTEGRAL (being an ESA mission) data.

4. Routine **teleconferences** and **consortium meetings** will be held, where all the members are invited to participate and present their work.
5. In addition, we will establish an **email list** for the distribution of generic information important for everyone, but also a number of **Slack channels** for quick, but archived and searchable communication on dedicated sub-topics.

Given that the size of the combined project group (6 scientists requested here for funding, plus about 8-10 scientists at the three institutes) is about 15 scientists, these management methods and communication channels are considered fully appropriate. There are very few management decisions to be taken, so more complex methods are not needed. For the administrative purposes, we do have support from our institute as well as the local EU office (see footnote of Table 3.1a).

(b) Innovation management

This activity, while proposed as a standalone project, is not defined by one (or more) parameter(s) or the preference of one (or more) astrophysicist(s), but is intended to serve as a tool for the larger community. High-energy data analysis is not as easy as many think, due to many subtle detector effects which change the properties of the measured count ensemble. Also, 20-year old ‘standard-tools’ (as presently available for INTEGRAL) cannot provide reliable results, as they are based on biased procedures or compute-power-saving mathematical procedures. One classical example is the iterative source removal in the INTEGRAL/SPI analysis (so-called spiros task), which introduces large systematic uncertainties for observations of weak sources. Polarization analysis is even more difficult as there are nearly no available tools to do this analysis. In addition, it requires computationally expensive simulations of how the instrument responds to polarization, which were not technically possible at the launch of the mission. The proper statistical treatment of soft gamma-ray polarization data is still in its infancy. (We have shown with the POLAR paper of how this could work, and why most of the previous things were badly designed, e.g. “150%” polarization!).

Since we intend to provide an XSPEC-like polarization analysis environment, including data acquisition from open-access data archives (INTEGRAL), for any user, we need to make sure that our tools will be accepted by the community. For this to happen, we will

- keep very tight contact to the INTEGRAL instrument teams,
- contact selected instrument team members to verify and approve our approach,
- provide jupyter-style demonstration analysis, so anyone can repeat our analysis within a day,
- get outside-the-box suggestions from our Advisory Board
- by enhancing our POLAR software package prepare the analysis tools for POLAR-2, so our deliverables can demonstrate to stand the test-of-life at the end of this activity (the launch of POLAR-2 is presently planned a few months before the end of this project)
- provide generic templates for other collaborations to include in their pipeline

This approach should guarantee that current and future instruments, capable of measuring polarization in the high-energy regime, will benefit immediately from our tools.

In Table 3.2a we list a number of milestones which will help us in the overall management to check for potential corrective measures of our activities. Obviously, all deliverables (as summarized in Table 3.1.c) also serve as milestones, in particular the planned documentation reports and publications towards the end of the project. The milestone table therefore concentrates more on the first half of the project lifetime. As a special quality assurance measure we have inserted a report by our Advisory Board after 12 and 14 months, respectively, which would provide us an external view of experts on how we are progressing.

(c) Risks

As science is the exploration of the unknown, any scientific endeavour is not without risk. Though, not discovering polarization in any of the sources/data that we explore is also an important finding which could have two reasons: (i) it is possible that with any statistically and physically robust framework which we develop, the data are not powerful enough to make a conclusive statement, or (ii) that our (the whole high-energy community) expectation for synchrotron radiation is wrong, and the actual emission mechanism may not produce polarized emission. One example for the former case could be SGRs: because of their soft spectra and the sub-dominance of Compton scattering at these low energies, we may not be able to measure polarization in the SGR emission. If indeed we find that no significant SGR polarization measurements are possible, we aim to provide both the tools to perform measurements using future missions as well as the theoretical ground-work to motivate such future measurements.

The POLCA team accepts these risk possibilities, but also recognizes that the value of properly developing a framework and new tools would already represent a major advancement. What we then conclude using the framework and tools, does belong to scientific endeavour: whatever we find, it will be scientifically interesting in itself, and motivating new follow-up research. Indeed, the first X-ray spectrometers developed did not possess the sensitivity or spectral resolution required to make definitive statements about emission processes. Nevertheless, the techniques (and partially software developed to analyze these data) are still of great value today. Similarly, the POLCA deliverables possess a long-standing value that provide a foundation for future instruments and experiments.

Another associated risk with the project is that in our research it may be impossible to locate and or fully replicate the response of some of the instruments in our study. In this case, the risk would be mitigated by using approximations for these responses which combine both our experience with the instrument themselves as well as gathered knowledge from other instruments in the studies. Nevertheless, such a lack of knowledge would have direct impacts on the quality of our results. This in turn can be used to inform the experimental design of future instruments. A managerial mitigation action that we have taken is to connect the INTEGRAL Project Scientist via our Advisory Board to the POLCA project. This ensures that the INTEGRAL project and its instrument teams are interested in our work, and that we have direct contact to all instrument specialists in case of questions.

3.3 Consortium as a whole

The POLCA Consortium brings together high-level expertise in different fields, mainly in high-energy astrophysics (both, observation and theory), computer science, and statistics, all focused on the same objective of fully exploiting data from the INTEGRAL mission to study the polarization of gamma-rays from cosmic sources. In particular, the MPE group (with the SPI co-PI) contributes INTEGRAL/SPI instrument details, the UNIGE group INTEGRAL/IBIS details. The expertise in the theory of jet sources resides with the TAU group. All groups have superior computer science expertise, and the MPE group involves one of the world-top statisticians. Thus, the members of the consortium are very complementary. The assignment of the tasks, and mostly also the work packages, simply follows this expertise, and uniquely defines the roles of each group (see Table 3.1a).

The following describes the contributions of each consortium member in somewhat more detail, and also lists the tasks for the requested personnel. Full details on the distribution of the sub-work-packages to the personnel is shown in the table above in sect. 3.1:

1. The MPE group will take the lead in the format specs, the statistical tools, and all the SPI studies (both software development as well as analysis). In addition, it will work on COMPTEL (built at MPE), and provide Fermi/GBM spectra for GAP-detected GRBs.
   The Post-Doc, during the first year, will work on the data and response format and the generic 3ML data and model interface. The next two years will be devoted to the SPI software development, and the last 6 months to the application to the COMPTEL data, and the interpretation of the data. The PhD student will fully work on the SPI data analysis.
2. The UNIGE group will contribute to the generic software development, in particular the polarization response generation, and take the lead in the IBIS studies (both software development as well as analysis). In addition, it will lead all tasks related to POLAR-1 and POLAR-2.
   The Post-Doc, during the first year, will work on the polarization response generation. The next two years will be devoted to the IBIS software development, and the last 6 months to the interpretation of the data. The PhD student will fully work on the IBIS data analysis.
3. The TAU group will perform all the theoretical studies including the development of an online tool for a later easy use by the community.
   The Post-Doc, during the first 2.5 years, will develop the code for the 3D matrices and the calculation of the surfaces of equal arrival time. The PhD student, during the first 2.5 years, will build the Monte-Carlo module, and add the radiation transfer effects and Compton scattering. In the last 1.5 years, both will work together in building the online GUI tool, connect it with the database, and apply the tool to the polarization data derived by the MPE and UNIGE groups.

3.4 Resources to be committed

For all participants, costs have been divided into direct and indirect costs. Direct costs have been split up into two types of costs: personnel costs and travel & other costs. Personnel costs have been calculated according to the individual personnel rates supplied by each partner administration. Since official rates do not exist yet beyond 2021, a 2% increase has been assumed. PhD students in Germany and Switzerland get about 300 Euro/month less in their first year, thus the difference between the first and second year is larger than 2%. The nominal duration of PhDs at MPE is presently 3.5 years, so we also budget only for 3.5 years.

The overall budget of the POLCA project over the full 48 months duration, as reported on the A3 form, is 1.894 MEur (incl. overhead). The total effort dedicated to the project is equal to 270 (requested from EC) + 175 (own contribution) = 445 person-months. The own contribution, detailed below under sub-section (c), corresponds to 1.397 MEur, implying a 40% share of the total costs of 3.3 MEur.

(a) Breakdown by type of activity

A percentage of total costs equal to ~98% (prior to overhead) will be allocated to the core RTD activities (including WP1-WP6). Dissemination activities (WP7, including implementation of a didactic projects) account for 2% of total costs. Management activities (WP0) are budgeted at 0% of the total costs (see footnote of table 3.1a).

(b) Breakdown by cost factor

The above mentioned resources will be integrated to give to POLCA the necessary critical mass to achieve the project milestones and deliverables. All the resources have been estimated analytically per cost category.

The net costs (without overhead) will cover:

Personnel costs (1,26 MEur, 85%): they represent the main share of the budget. The allocation of person-months to the different partners reflects the activities they will carry out within the project. The overall effort of the project is 445 person months, 270 for new personnel hired specifically for the implementation of the project, with different levels of qualification and experience according to different needs, and 175 from the personnel working in the different partner organizations (see table below).

Other direct costs (254.300 Euro, 15%): they include:

Travel costs (12.000 Euro per node) provide, for each partner, the necessary budget for participating to the pre-planned project meetings (Kick-off at Month 1, Consortium meetings at months 12, 24 and 36, as well as a final informal meeting during an International Workshop dedicated to the release of our products to the Community). Although we will make extensive use of teleconference systems as well as of Web-based information exchange systems, we also foresee temporary visits and exchange of researchers between the participating sites. We budget 750 Euro per flight, 120 Euro per night accommodation, and 30 Euro daily allowance, i.e. 1500 Euro per 5-day visit of one person. We account for 4 travels per node (for 2 of the 6 travels, each participant will be the host of the meeting), for each of the two EU-funded scientists. The share of the travel costs for dissemination activities, i.e. allowing partners to participate at conferences in order to present the status and the results, as well as the travel costs for the institutional team members, will be covered by the institutions.

Equipment costs (188.500 Euro) include hardware to the spectrometer for POLAR-2. This exclusively covers the extra costs for the add-on detector (see table below for details) in order to allow the measurement of the GRB position and spectrum. We do not request support for computing facilities: Computer hardware (workstations and PCs) will be covered by the host institutions. Also, core data analysis will be performed on high performance computing facilities already available to the partner institutions.

Gold Open access: As described above (sect. 2.2), we only budget for two theoretical publications (assigned to TAU) which are not covered by the EDS publication rules and/or the special contracts with the Max-Planck Society. We use the latest number available (i.e. 2019 EDS price): 1900 Euro per publication.

Other direct costs (26.000 Euro): 10.000 Euro are requested for UNIGE for the organization of the final International Workshop in Switzerland (mainly aimed at covering expenses for invited speakers). 2.000 Euro are requested for each participant to prepare material (booklets, handbooks, flyers) for didactic activity in our 3 countries, as well as for outreach to general audience (Astronomy-on-tap, etc). Since for direct costs per participant exceeding 375 kEur, an audit is required at the end of the project, we include the corresponding costs (5000 Eur for MPE and UNIGE).

Hardware costs for POLAR-2 spectrometer:

Packaged CeBr3 scintillation crystals, 10 cm x 10 cm per piece, 2x2 pieces per module, 4 modules: in total 16 pieces (14 kEur per piece, Scionix offer)	224.00 kEur
SiPM arrays, 4 per scintillation crystal, 16 in total (2.5 kEur per piece; SENSL offer)	40.00 kEur
64 channel ASIC read-out (identical to polarimeter ASIC, will be provided by UNIGE group)	0.00 kEur
19% Tax	50.16 kEur
60% of 314.16 kEur Sum (corresponding to the total budget funding ratio)	188.50 kEur

Below is a summary of the direct costs as detailed above:

		MPE	UNIGE	TAU
Personnel	Post-doc	304.500	344.000	144.200
	PhD	159.500	204.000	105.100
Travel		12.000	12.000	12.000
Equipment		188.500		
Final conference			10.000	
Audit		5.000	5.000	
Outreach		2.000	2.000	2.000
Publication				3.800
Sum (w/o overhead)		671.500	577.000	267.100

(c) Partner's resources complementing the EC contribution

The main contribution provided by participants are (i) the personnel costs of the institutional team members, (ii) travel money of the institutional team members, and (iii) the use and share of their own laboratories and facilities to carry out the foreseen research activities, in particular the high performance computing facilities needed to carry out the systematic analysis and simulation of the instrument responses. A rough estimate gives 1.397 MEur; a break-down is given in the table below.

	Institutional Personnell & costs (kEur / year) times the fraction spend for the project		Travel cost for institutional team members (kEur / year)	Cost of Resources (kEur / year)
MPE	Greiner	120x30%	2.7	10
	Burgess	90x50%	2.7	10
UNIGE	Kole	110x30%	2.7	10
	UNIGE-Post-Doc	100x30%	2.7	
	PhD student	75x100%	2.7	
TAU	Bromberg	40x30%	2.7	10
	Nakar	50x15%	2.7	10
	PhD student	25x100%	2.7	

Tables for section 3.1

Table 3.1a: List of work packages

The two positions at MPE and one position at Geneva are planned for a duration of 3.5 yrs, the other for 4 yrs each. This sums up to a total of 270 person-months.

Work package No	Work Package Title	Lead Participant No	Lead Participant Short Name	Person-Months	Start Month	End month
0	Management	1	MPE	0[a]	1	48
1	Software development	1	MPE	21	1	20
2	IBIS	2	UNIGE	68	10	34
3	SPI	1	MPE	62	10	34
4	Archival analysis	2	UNIGE	12	34	43
5	Theoretical Modelling	3	TAU	95	1	48
6	Past and Future	2	UNIGE	9	43	48
7	Outreach	3	TAU	3	1	48
				Total person-months: 270		

(b) The management task will be fulfilled by the project coordinator (scientific parts), MPE administration (funding and administrative management) and the EU office of the Max-Planck Society (which resides on the same campus as MPE), and not charged to any of the six scientists to be funded through the EU.

Table 3.1b: Work package description

Work package number	0	**Lead beneficiary**			MPE		
Work package title	Management						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TAU				
Person months per participant:	0	0	0				
Start month	1			**End month**	48		

Objectives: Guarantee the execution of the scheduled tasks, the creation of the deliverables, the interactions of all parties involved, and the timely reporting to the EC. The task will be shared between the Project coordinator, MPE administration, and the Bavarian EU office representative.

Description of work

This WP is led by the project coordinator (PC), supported by the team leaders of the other two participating institutions, and the administrative staff of the hosting institutes. The main tasks are the following:

Task 0.1: Project Management (coordination and monitoring): The administrative coordination between the different participants will be guaranteed mainly through routine teleconferences, Slack channels, and yearly Consortium meeting. A password restricted area of the POLCA website will be created and maintained as repository of internal documentations.

Task 0.2: Financial management: Organize the budget and cash flow plan, produce the required financial reports according to EU requirements.

Task 0.3: Advisory Board (AB): Maintain communication with the Advisory Board in both directions (inform AB about progress; receive suggestions/criticism from AB).

Task 0.4: Interface between partners and Commission: Activate administrative procedures relating the participant partners and preparation of the required reports according to EU requirements. To officially start the project, a kick-off meeting with the Consortium and the EC will be organized.

Task 0.5: Innovation Management: Organize discussions and decision-making process for final delivery of tools and data products to ESA. Guarantee appropriate instructions for use by external groups. Prepare follow-up use by POLAR-2 team.

Deliverables

D0.1 First year administrative/financial report (T_o + 12 months)

D0.2 Second year administrative/financial report (T_o + 24 months)

D0.3 Final administrative/financial report (T_o + 48 months)

Work package number	1	**Lead beneficiary**			MPE			
Work package title	Software Development							
Participant number	1	2	3					
Short name of participant	MPE	UNIGE	TAU					
Person months per participant:	12	9	0					
Start month	1			**End month**	20			

Objectives: Design polarization data format and develop software for the analysis of IBIS&SPI and the corresponding interfaces (3ML, archive, VO).

Description of work

Task 1: Polarization data format: design and implement a universal data format for high-energy polarization data

Task 2: Polarization response format: design and implement a format and technique to parameterize a polarization response matrix for universal distribution and usage

Task 3: Virtual-Observatory: create an online repository for our data products with interfaces to the Virtual Observatory (VO) protocol

Task 4: 3ML plugin: preliminary design and implementation of generic 3ML data and model interface

Task 5: Polarization statistical likelihoods: Derive the appropriate data likelihoods for each instrument in the study as well as a generic statistical framework for future instruments

Task 6: Energy-resolved polarization analysis: Technical conceptual design of energy-resolved polarization approach and software

Task 7: Proof-of-concept with POLAR GRB data: applying the full methodology and software

Task 8: Documentation: Online software manual with worked examples for the usage of all components of WP1. WP2, WP3

Deliverables

D1.1 Delivery of statistics code for 3ML implementation. (T_o + 4 months)

D1.2 3ML framework (T_o +9 months)

D1.3 Energy dependent polarization analysis tools documentation (T_o+12 months)

D1.4 Formalized polarization data format documentation (T_o+15 months)

D1.5 Formalized polarization response format documentation (T_o+18 months)

D1.6 Publication of formalized POLAR polarization data & response (T_o + 20 months)

D1.7 Publish re-analysis of all POLAR GRBs, incl. energy-dependent polarization (T_o+20 mo)

D1.8 Software Manual (T_o + 48months; formally outside the liefetime of the WP, but it should be one document including s/w from WPs 2 and 3 as well.)

Work package number	2	**Lead beneficiary**		UNIGE			
Work package title	Polarization with the INTEGRAL/IBIS instrument						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TAU				
Person months per participant:	2	66	0				
Start month	10			**End month**	34		

Objectives: Simulation and calibration of the instrument modes, and generation of polarization response matrices. Preparation of the plugin for 3ML. Preparation of the software for the polarization analysis, including a completely new method with ISGRI-only Compton-scattered events.

Description of work

Task 1: Calibration: Simulate energy-dependent polarization response, cross-correlate with Crab results (spectrum, normalization); determine predicted modulation as function of energy
Task 2: Response generation of ISGRI/PICsIT Compton mode response; assessment of mal-functioning pixels over time; include degradation of detecting pixels over mission years
Task 3: Response generation of ISGRI-only polarization measurement method; consistently simulate and evaluate timing distribution of mask-shadowed pixels
Task 4: Plugin for 3ML
Task 5: Polarization analysis part I: "canonical" analysis in Compton mode using ISGRI and PICsIT for short- and long-term sources; validate standard software background
Task 6: Polarization analysis part II: construct background model for ISGRI-only method, based on time selections and modules used

Deliverables

D2.1 list of sources for which IBIS/SPI polarization analysis will be made. (T_o+10 mo)

D2.2 Creation of simulated polarization response. (T_o+24 mo)

D2.3 3ML plugin. (T_o+ 30 mo)

D2.4 Software package for canonical ISGRI-PICsIT analysis. (T_o+30 mo)

D2.5 Software package for new method. (T_o+34 mo)

Work package number	3		Lead beneficiary			MPE	
Work package title	Polarization with the INTEGRAL/SPI instrument						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TAU				
Person months per participant:	57	4	0				
Start month	10			**End month**	34		

Objectives: Simulation and calibration of the instrument modes, and generation of polarization response matrices. Preparation of the plugin for 3ML. Preparation of the software for the polarization analysis.

Description of work

Task 1: Calibration: Simulate energy-dependent polarization response, cross-correlate with Crab results (spectrum, normalization); Determine predicted modulation as function of energy

Task 2: Response generation: Over time, 4 of the 19 detectors failed, so there are 5 detector configurations for which a response has to be derived via simulations; utilize full SPI data space of multiple detection events (triple, quadruple, …) for additional information

Task 3: construct long-term background model for polarization analysis (evolution of previous concept)

Task 4: Plugin for 3ML

Task 5: Polarization analysis of short-term (short and long GRBs) and long-term (pulsars, Crab, ...) sources; spectro-polarimetric and temporal models

Deliverables

D3.1 List of sources for which SPI polarization analysis will be made. (T_o+10 mo)

D3.2 Creation of simulated polarization response. (T_o+24 mo)

D3.3 3ML plugin. (T_o+ 30 mo)

D3.4 Software package for polarization analysis. (T_o+34 mo)

Work package number	4	**Lead beneficiary**			UNIGE		
Work package title	Archival Analysis of published sources						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TAU				
Person months per participant:	6	5	2				
Start month	34			**End month**	43		

Objectives: This WP is lead by the UNIGE group who previously lead the analysis of the POLAR-1 data. The WP will ensure reanalysis of already published data from POLAR, GAP, the INTEGRAL instruments and any additional instruments if possible. This study serves to both qualify the newly developed methodology as well as to produce new scientific results. Additionally, analysis will be performed on previously not analyzed sources using data from these instruments.

Description of work

Task 1: Gamma-Ray Bursts (GRBs): Data from both INTEGRAL instruments as well as that from GAP will be used together with the new analysis method to perform the first multi-instrument polarization studies. Where possible time- and energy-resolved polarization studies will be done.

Task 2: Soft Gamma Repeaters (SGRs): A list of all possible SGRs visible by any of the above mentioned instruments will be composed. Subsequently polarization analysis will be performed for all SGRs in this list. Where possible time- and energy-resolved polarization studies will be done.

Task 4: Bright steady sources (Crab / Cyg X-1): Non-imaging instruments (GAP, POLAR-1) can not be used for steady sources, while data from both INTEGRAL instruments can be used to analyze all kind of sources. Due to their steady states, these sources will allow for multi-instrument analysis. Where possible time- and energy-resolved polarization studies will be done.

Task 5: Transients (V404 Cyg, GRS 1915+105, Cen A etc.): All the above instruments are capable of performing polarization measurements of transients (if in their field of view). A list of possible transients observed by all the instruments will be compiled, followed by polarization analysis of these transients. Where possible time- and energy-resolved polarization studies will be done.

Deliverables

D4.1 List of all sources observed by any instrument with polarization capabilities (T_o+34 months)

D4.2 Sci. publication of re-analysis of GRBs from INTEGRAL instruments (T_o+40 months)

D4.3 Publication of GAP data & response in formalized format, and GRB re-analysis (T_o+40 mo)

D4.4 Sci. publication on SGR polarization measurements using new analysis method (T_o+43 mo)

D4.5 Sci. publication on Bright Steady Sources polarization measurements using new analysis method (T_o+43 months)

D4.6 Sci. publication on transient polarization measurements using new method (T_o+43 mo)

Work package number	5	**Lead beneficiary**			TAU		
Work package title	Theoretical Modelling of Polarization in Astrophysical Sources						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TAU				
Person months per participant:	1	1	93				
Start month	1			**End month**	48		

Objectives: This WP is led by the TAU group and will develop theoretical models for the expected polarization properties of our sources, based on present-day knowledge of the jet physics which is thought to play the dominant role.

Description of work

Task 1: Expand the existing code to include 3D matrices and efficient calculation of the surfaces of equal arrival time.
Task 2: Implementation of the Monte-Carlo module and the radiation transfer effects that will be accounted for.
Task 3: Development of a GUI that will allow the code to be accessible to the public via an online platform. The platform will be connected with a resource that will include the observational data from the project and will allow an independent analysis of the data.

Task 4: With the proposed extension our model will be applicable to a wider range of sources, thus the theoretical framework developed here in WP5 will be applied to the data of the different source types as deduced in WP4 and WP6.

Deliverables

D5.1 Theoretical modelling paper; overview paper of emission mechanisms and resulting spectro-polarimetric emission, also as a function of time (T_o+12 mo)

D5.2 Fully operational 3D code without radiation transport (T_o+24 mo)

D5.3 Building MC and radiation transfer effects and connecting it with 3D code (T_o+36 mo)

D5.4 Develop an Online GUI connecting the new theoretical model with the data base. (T_o+36mo)

D5.5 Publication with the scientific results of applying the new theoretical description to the INTEGRAL data. (T_o+48 mo)

Work package number	6	Lead beneficiary			UNIGE		
Work package title	Application						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TAU				
Person months per participant:	5	4	0				
Start month	43			**End month**	48		

Objectives: This WP has the goal of ensuring application of the work developed during the project after the funding finishes. For this purpose, it aims to produce the tools to make use of existing data and advertising these products, to produce the tools required to ensure the application in a future mission and finally to optimize a future mission for applying the products and findings.

Description of work

Task 1: Past instruments with strong European contribution: The WP1 and WP5 products will be used to provide a foundation for re-analysis of data from past instrumentation. An example is COMPTEL (CGRO), which will firstly be used to produce the data format defined in WP1 while also an instrument response is produced using the same format. The data, response and available models will be detailed in a dedicated publication, thereby advertising its use to the wider community ensuring future use.

Task 2: POLAR-2 as a first costumer: With a launch in 2024, soon after this project finishes, POLAR-2 forms an ideal candidate as a first customer. This WP will prepare the instrument response and the pipeline to produce the POLAR-2 data in the format defined by WP1, thereby ensuring direct use of the products developed in the project.

Task 3: Hardware contribution to POLAR-2 (spectrometer): This WP will develop a spectrometer to be placed on the POLAR-2 mission with the aim of optimizing the capability to perform joined spectral and polarization analysis.

Deliverables

D6.1 Document describing COMPTEL data and response in formalized format (T_o+45 mo)

D6.2 Publication of all COMPTEL data, response and analysis to general public (T_o+48 mo)

D6.3 Publication of POLAR-2 data products and response in formalized format (T_o+48 mo)

D6.4 Technical design report of POLAR-2 spectrometer (T_o+12 mo; this is formally prior to the start of this WP, but obviously is a requirement before purchasing the scintillators)

Work package number	7	**Lead beneficiary**			TAU		
Work package title	Outreach and Dissemination						
Participant number	1	2	3				
Short name of participant	MPE	UNIGE	TAU				
Person months per participant:	1	1	1				
Start month	1			**End month**	48		

Objectives: Make sure that our results and products are disseminated to both, to the scientific community, and the wider audience. Enable exploitation of the results and tools for future missions. Organize events to inform the public about our main astrophysical new insight.

Description of work

Task 1: Dissemination of results and software tools to the astrophysical community by special conferences, workshops, or Hands-on courses, or corresponding contributions towards this goal to large-audience conferences. Prepare exploitation of results for future projects.

Task 2: Communication activities, i.e. outreach via a variety of channels, incl. news papers, social media, and the Internet in general (dedicated Web-pages).

Task 3: Scientific Publications: Our main results, both technical (data format, data analysis methodology, software) as well as scientific (actual polarization measurements of astrophysical sources) shall be published in the refereed literature, and made publicly available under the Gold Open access rules.

Deliverables

D7.1 Provide ESA/ESOC with requirements to include polarization parameters in their database and query forms. (T_o+ 3 months)

D7.2 Establish Data Management Plan for making our data and software findable, accessible, interoperable and reusable (FAIR). (To+ 6 months; and following periodic and final reports)

D7.3 Reach out to AHEAD and formulate synergetic aspects for calibration of INTEGRAL instruments. (T_o+ 6 months)

D7.4 Update plan for dissemination and exploitation of the projects results. (T_o+ 9 months)

D7.5 Reports on outreach activities. (T_o+ 24 months and 48 months)

D7.6 Scientific papers on results not covered in the individual WPs (see detailed version in the other WPs). (T_o+ 48 months)

Table 3.1c: List of Deliverables

The following deliverables are listed according to the time of delivery, not WP sequence. Some software releases are marked as CO (confidential): this is meant to be confidential only for the duration of the project. Pola = Polarization, resp = response, Publ = publication, Rep = Report

Deliverable (number)	Deliverable name	WP #	Short name of lead participant	Type	Dissemi-nation level	Delivery date (in months)
7.1	Database & query Req	7	MPE	R	PU	3
1.1	Statistics code	1	MPE	OTHER	PU	4
7.2	Data management plan	1	MPE	R	PU	6
7.3	AHEAD synergy	7	MPE	R	PU	6
1.2	3ML adaptation	1	MPE	OTHER	PU	9
7.4	Dissemination plan	7	TAU	R	PU	9
2.1	List of IBIS sources	2	UNIGE	R	PU	10
3.1	List of SPI sources	3	MPE	R	PU	10
1.3	Energy-dependent pola documentation	4	UNIGE	R	PU	12
6.4	POLAR-2 spectrometer	6	MPE	R	PU	12
5.1	Theory publication	5	TAU	R	PU	12
1.4	Pola data format	1	MPE	R	PU	15
1.5	Pola response format	1	MPE	R	PU	18
1.6	Publ POLAR data & response	4	UNIGE	OTHER	PU	20
1.7	Publ POLAR GRBs	4	UNIGE	R	PU	20
7.5a	Rep outreach activities	7	TAU	R	PU	24
2.2	Simulated IBIS pola resp	2	UNIGE	OTHER	CO	24
3.2	Simulated SPI pola resp	3	MPE	OTHER	CO	24
5.2	3D code w/o radiation	5	TAU	OTHER	CO	24
2.3	IBIS 3ML plugin	2	UNIGE	OTHER	PU	30
3.3	SPI 3ML plugin	3	MPE	OTHER	PU	30
2.4	Software ISGRI-PICsIT	2	UNIGE	OTHER	CO	30
2.5	Software ISGRI-only	2	UNIGE	OTHER	CO	34
3.4	Software SPI	3	MPE	OTHER	CO	34
4.1	List of all sources	4	UNIGE	R	PU	34
5.3	MC & radiation transfer	5	TAU	OTHER	CO	36
5.4	Theory Online GUI	5	TAU	OTHER	CO	36
4.2	Publ Pola of INTEGRAL GRBs	4	UNIGE	R	PU	40
4.3	Publ re-analysis GAP GRBs	4	UNIGE	R	PU	40

4.4	Publ Pola of INTEGRAL SGRs	4	UNIGE	R	PU	43
4.5	Publ pola INTEGRAL bright sources	4	UNIGE	R	PU	43
4.6	Publ Pola of INTEGRAL transients	4	UNIGE	R	PU	43
6.1	COMPTEL data & resp	6	UNIGE	R	PU	45
1.8	Software Manual	1	MPE	R	PU	48
5.5	Publ pola theory applied to new data	5	TAU	R	PU	48
6.2	Publ pola of COMPTEL sources	6	MPE	R	PU	48
6.3	Publ POLAR-2 data & resp format	6	UNIGE	R	PU	48
7.5b	Rep outreach activities	7	TAU	R	PU	48
7.6	Publ scientific results	7	MPE	R	PU	48

KEY: *Deliverable numbers in order of delivery dates. Please use the numbering convention <WP number>.<number of deliverable within that WP>.*

Type: *Use one of the following codes:*
R: Document, report (excluding the periodic and final reports)
DEM: Demonstrator, pilot, prototype, plan designs
DEC: Websites, patents filing, press & media actions, videos, etc.
OTHER: Software, technical diagram, etc.
Dissemination level: *Use one of the following codes:*
PU = Public, fully open, e.g. web
CO = Confidential, restricted under conditions set out in Model Grant Agreement
CI = Classified, information as referred to in Commission Decision 2001/844/EC.
Delivery date: Measured in months from the project start date (month 1)

Tables for section 3.2

Table 3.2a: List of milestones

Milestone number	Milestone name	Related work package(s)	Due date (in month)	Means of verification
0	Kick-off	0-7	0	Meeting held
1	establish s/w infra-structure (github)	1,3,4,5	2	link to github established
2	VO interface	1	4	s/w released and validated
3	Plugin design	1	4	polarpy prototype demo
4	3ML Statistics code	1	4	s/w released and validated
5	Framework for simulation work	1,3,4	6	s/w released and validated
6	Concept energy-resolved pola	1	10	s/w designed
7	Pola format defined	1	12	Community Document
8	Adv Board Report	1-7	12	Meeting with AB
9	Resp format defined	1	15	Community Document
10	Generic s/w ready	1	24	Meeting held
11	Pola simulations	2	24	s/w released and validated
12	Adv Board Report	1-7	24	Meeting with AB
13	Instrument s/w review	3,4	34	s/w released and validated
14	Demonstration of full analysis	2,3,4	43	Publications on GRBs and Crab submitted

Due date: *Measured in months from the project start date (month 1)*

Means of verification: *Show how you will confirm that the milestone has been attained. Refer to indicators if appropriate. For example: a laboratory prototype that is 'up and running'; software released and validated by a user group; field survey complete and data quality validated.*

Table 3.2b: Critical risks for implementation

Description of risk (indicate level of likelihood: Low/Medium/High)	Work package(s) involved	Proposed risk-mitigation measures
Lack of particular instrument details relevant for polarization (low risk)	2,3,4	INTEGRAL Project Scientist and IBIS specialist in Advisory Board; SPI specialist in the team

Definition critical risk:
A critical risk is a plausible event or issue that could have a high adverse impact on the ability of the project to achieve its objectives.

Level of likelihood *to occur:* **Low/medium/high**
The likelihood is the estimated probability that the risk will materialise even after taking account of the mitigating measures put in place.

Tables for section 3.4

Table 3.4a: Summary of staff effort

Below is the summary table of the distribution of person-months over the work packages for each of the three participants as requested through EU funding. The own institutional contribution of each participant is given in the table under sect. 3.4. Note that the "Management" in WP0 will be provided by the Project Coordinator, and not charged to the EU.

	WP0	WP1	WP2	WP3	WP4	WP5	WP6	WP7	Total Person-Months per Participant
1 / MPG	**0**	**12**	2	**57**	6	1	5	1	84
2 / UNIGE	0	9	**66**	4	**5**	1	**4**	1	90
3 / TAU	0	0	0	0	2	**93**	0	1	96
Total Person Months	0	21	68	61	13	95	9	3	(270)

Table 3.4b: 'Other direct cost' items (travel, equipment, other goods and services, large research infrastructure)

Travel and outreach costs are the same for each participant. For the other two participants, the direct other costs are far below the 15% limit for this table, so are not specified here. MPE and UNIGE benefit in the same way from the POLAR-2 hardware costs, but for honesty reasons the total sum is listed here under one participant (instead of splitting it).

1 / MPE	Cost (€)	Justification
Travel	12.000	4 travels (see text for break-down)
Equipment	188.500	Invest for POLAR-2 spectrometer
Other goods and services	7.000	2000 for outreach and didactic material; 5000 for audit
Total	207.500	

Participant Number/Short Name	Cost (€)	Justification
Large research infrastructure	n/a	