Towards the SKA and CTA era: discovery, localisation, and physics of transient sources

SKA-CTA joint project

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Abstract

(at the end)

1. **General science context, national and international** (max 4pg)

"Transient" sources are astrophysical objects that explode or flare up in violent and unpredictable way. They can be of galactic or extragalactic origin, can emit coherent or incoherent radiation and even non electromagnetic signals, and can be the result of thermal runaways, explosions, and particle acceleration. Variability time scales, released energy, wavelength of the emitted radiation can vary widely depending on the nature of the progenitor and of the physical process. In general, they are associated with catastrophic events involving compact objects, such as white dwarves, neutron stars, and black holes, and as such they offer the possibility to study the most extreme physical conditions in the Universe. Furthermore, their sometimes extreme luminosities make them invaluable cosmic probes of the medium and the background light.

The study of transient astrophysical sources is now entering a golden age. Among the most cited astrophysics papers in the last year, we find the discovery of a >5.1σ transient GW signal by aLIGO [1], with a plethora of follow-up interpretative and multi-wavelength observational papers; the debate about the first possible extragalactic localisation of a FRB [2, 3], as well as the discovery and identification of the first repeating FRB [4, 5]; (3) the appearance of new theory- and observation-based population studies of TDE rates [6, 7]. In more developed fields, some truly remarkable events have also been reported, such as a giant flare of the XRB Cyg X-3. Each of these results has far-reaching implications both for the study of the physical processes at the origin of the transients themselves (the mass of the merging BHs for the GW event, the luminosity and the possible progenitor type for the FRB, the temperature and density of the TDE event) and for more general topics that can be probed through these discoveries (eg, the rate of binary BH mergers and their formation from massive stars in low-metallicity environments, the average cosmic density of ionised baryons in the intergalactic medium, the supermassive BH mass function).

Radio waves and gamma rays are both crucial, in a complementary fashion, to the study of transient phenomena. Radio waves have the key advantages of measuring kinetic feedback in relativistically moving ejecta, of probing the properties of the intervening ionised media, and of a precise localisation across wide fields of view [8]. Gamma rays on the other hand directly trace the highest energy particles, *their acceleration and emission processes,)* and are probes of EBL and LIV. As progress is being made towards the construction of SKA and CTA, as well as the operation of their pathfinders, precursors, and prototypes, it is becoming increasingly clear how their characteristics will be of fundamental importance for the discovery, localisation, and understanding of transient sources. By comparison to the present day facilities at the same wavelength, both instruments will have a larger field of view, a higher sensitivity, and a better capability of promptly react to triggers. These features will allow us to dramatically increase the number of detected transients and the level of details in which they could be studied. Indeed, "transients" are one of CTA's key science projects (KSP) and the prime subject of science working groups (WG) both in CTA and SKA. Other wavelengths and multi-messenger observations will also contribute to the advance of this field. It is thus mandatory to start preparing the national community with a

List of acronyms

CTA	Cherenkov Telescope Array	GRB	gamma ray burst	BH	black hole	aLIGO	Advanced Laser Interferometers GW Observatory
SKA	Square Kilometre Array	XRB	X-ray binary	NS	neutron star	AdV	Advanced Virgo
GW	gravitational waves	SN	supernova	WD	white dwarf	MWL	multi-wavelength
FRB	fast radio burst	TDE	tidal disruption event	MM	multi-messenger	EM	electromagnetic
EBL	extragalactic background light	LIV	Lorentz invariance violation				

coordinated program based on the preparatory radio and gamma-ray facilities, on complementary EM and GW facilities, and on the theoretical, modelling, and numerical side.

Within the present proposal, we intend to develop a common framework to deal with the large variety of transient phenomena: depending on the type of progenitor, the energy band and type of radiation through which they were discovered, and the relative time and space frequency, our present understanding of the different types of transients varies broadly. Having discovered >10^3 GRB, we know a greater deal about them in comparison to the dozen or so FRB, for which it is still debated whether they are of galactic or extragalactic origin. There are however strong observational and interpretative connections between the various areas: finding the counterpart to GW events requires a deep understanding of the features of known transients such as binaries and short GRBs, formulating predictions on orphan afterglows also depends on models developed for known GRBs on-axis, localising a FRB or GW event have many steps necessarily in common; most transients are inherently MWL emitters. Several scientists in our team are active in more than one of these fields and the composition of the team is balanced between people already involved in the science/technology development of SKA and CTA and those willing to contribute to and support the scientific exploitation of their data. The most efficient approach is thus to gather the community in a single comprehensive, coordinated proposal. In the following, we outline the state of the art for the main classes of transients (1.1), the role of CTA (1.2), and SKA (1.3). In the goal section, we will define the actual work packages and actions for our project, highlighting the synergies among groups and topics.

1.1 Targets of interest

September 14, 2015, marked the official start of the gravitational astronomy era, with the first detection of **GW** achieved by the aLIGO and AdV collaboration [9]. Realistic detection rate by 2020 is of dozens up to hundreds of GW sources per year in the high frequency range accessible to ground-based interferometers (10-1000 Hz), with sky localisations of the order of 10 square degrees or less [10]. EM counterparts of GW sources will enable to increase sky localisation accuracy and to provide a wealth of additional/complementary information on the source nature. Primary candidate GW+EM sources in the era of ground-based laser interferometers as aLIGO and AdV are coalescing binary systems of compact objects as stellar-mass BH and NS. These systems are the best candidate progenitors of EM events as short GRBs [11]. Other sources as core-collapsing SNe and instability phenomena from NS may also be detected in the high frequency GW spectrum although with larger uncertainties on their energy output. Sources of unknown nature might be identified too.

GRBs, the most luminous transients detected up to extremely high redshifts, are characterised by a prompt highly variable emission at high energies, followed by a smoothly decaying afterglow observed from the X-rays to the radio wavelengths [12]. Increasing observational evidence corroborates the general picture of GRBs being the EM signatures of relativistic jets launched by BHs or massive, highly magnetised, NS. Observations have been collected from >10 GeV to the radio band covering the prompt and the afterglow timescales; in particular, optical photometry and spectroscopy have demonstrated that long GRBs are tied to the death of massive stars and in particular to a small fraction of very luminous core-collapse SNe. However, there are still several compelling questions on the physical mechanisms at work in GRBs and on their origin. The search for and the study of **SNe** explosions themselves in general have focused on the observation and analysis of the spectral energy distribution (SED) in the optical range for decades; as observations at other wavelengths are becoming available, they contribute to the knowledge of the SN explosion mechanisms and the characterisation of the SN precursors, which in turn are critical for our understanding of the final evolution of SNe progenitors, of their recent history of mass loss, and of long GRBs. However, radio detections of both GRBs and SNe are rare (<30%), and neither class has been secured a detection above 100 GeV so far.

The issue of localisation is crucial also in the case of **FRB**, unpredictable GHz frequencies bursts characterised by millisecond duration and high dispersion measure. A large number of models have been proposed, both galactic and extragalactic, with the large DM favouring the latter scenario. As the events are short and unpredictable, they are generally detected with a large positional uncertainty and the debate about an accurate localisation has been one of the hottest threads in the last year [2, 3, 13]. The discovery of one repeating event has permitted to follow it up interferometry, and at least in that particular case the event seems to be extragalactic and associated with a dwarf galaxy at z ~ 0.2 [5]. This has tremendous implications for the progenitor and for probing the cosmic density of ionised baryons. Many open questions remain however, such as the nature of the progenitors, whether repeating and non-repeating FRBs have the same origin or form two different classes, the presence of high energy emission. Given the high number of events (up to 10^4/sky/day), there is tremendous space for discovery in this field.

Another class of sources that at present is mainly discovered in the optical and X-rays, but for which radio and VHE observations hold great potential is that of **TDE**. TDEs are unique laboratories to study the physics of accretion onto massive/supermassive BH lively. Transient emission mainly in the optical to X-rays is produced when a star or gas cloud is gravitationally disrupted and swallowed through the formation of an accretion disk around BH at the center of galaxies [14]. This relatively young and unexplored class of high energy transients is extremely promising in revealing the stellar dynamics closest to the central galaxy monsters. 10% of TDE should have a jet and share properties of other relativistic jetted sources. High and very high energy emission is expected for jetted and non-jetted TDEs [15] but such prediction is still to be tested. Open questions in this field are overwhelmingly more compelling due to the lack of MW observations and the present small statistics of events.

Within our own Galaxy, transient emission is detected from many binary systems, both composed of two compact objects (millisecond pulsar binaries) or of one compact and one stellar object (novae, micro-quasars). Many of these sources have shown surprises: symbiotic and classical novae have been revealed as a new class of gamma-ray emitters by Fermi [16, 17], indicating that they are sites of particle acceleration, and interferometric radio observations have demonstrated the possibility to study the spatial and spectral evolution of the emitting region [18, 19]. Millisecond pulsar binaries accreting at very low-rates have been recently found to surprisingly emit at radio and GeV energies and to transit from disk to a disk-free states on months-yrs timescales [20, 21]; analogously, the unique WD binary AE Aqr has shown bright radio flares and a puzzling high energy behaviour, with both detections and upper limits [22]; such systems in which accretion disks exist but are only partially feeding the accreting fast spinning compact object, as well as micro-quasars in which transient radio and gamma-ray emission is detected, are crucial in understanding the accretion/ejection coupling on much shorter timescales than those permitted by blazars. This includes the outstanding cases of Cyg X-1, Cyg X-3, V404 Cyg (), as well as the high mass X-ray binaries detected in the MeV-TeV energy band, which prove that an efficient, yet far from being understood, mechanism is in place and accelerates particles up to a few tens of TeV. Current models involve both leptonic scenarios (gamma-ray production from inverse Compton scattering between the jet electrons and stellar/synchrotron photons) and hadronic scenarios (from *p-p* interactions between relativistic jet hadrons and cold stellar wind protons or nuclei).

1.2 Transients & (very) high energy emission

The design of CTA offers several important characteristics that will greatly benefit the study of transients: great sensitivity over a broad energy range thanks to the three telescope sizes, capability of fast repointing, and a large area survey mode provided by divergent pointing observations.

Moreover, the nature of the gamma-ray sky itself, with a paucity of sources with respect e.g. to optical sky, could play a crucial role in detecting the EM counterpart of a GW event: CTA could quickly (<1 ks) cover large regions of the sky by operating in survey mode with good sensitivity without being contaminated by thousands of false positives as in the optical [5,6,7]. CTA detection of the EM counterpart would enhance source localisation accuracy thus enabling further monitoring with telescopes at longer wavelengths. CTA detection of a short GRB associated with a GW signal from compact binary systems will directly confirm the progenitor nature of this class of astrophysical sources. At the same time, detection of unidentified VHE transient sources can be searched off-line on archival GW data by exploiting the resultant known sky location and event time. This strategy is for example actually carried on by the aLIGO/Virgo Collaborations to understand the nature of FRB.

High sensitivity and high temporal/spectral resolution studies by CTA will contribute to understand the emission mechanisms for many other transients which are anticipated to be detected above few tens of GeV: binaries, TDEs, GRBs. For GRBs in particular, the results by Fermi [23] indicate that CTA will be crucial to reveal the prompt emission radiation mechanism (leptonic vs hadronic), the energy dissipation site (internal/external), the jet composition (magnetic/baryons) and its acceleration and collimation mechanism (magnetic or stellar envelope), the total energy involved, the transition from the prompt to the afterglow phase. CTA will probe the role of GRBs as sources of UHECRs and neutrinos and will use GRBs to constrain the EBL at intermediate and high redshifts and to study LIV through the expected energy dependence of photon arrival times [24]. Some of these open issues are directly related to the nature of the progenitors and central engine of both long and short GRBs.

1.3 Transients & radio emission

All the classes of sources described above are radio emitters at some level, so the impact of SKA and its precursors will be huge in all areas. The key elements will be the sensitivity, the wide field of view and frequency range, the highly advanced signal processing and data management techniques required to detect transients on very short time scales and large dispersion measures, and the possibility to operate in VLBI mode for ultra-high angular resolution imaging capabilities.

SKA observations of GRBs will uniquely probe the GRB emission and the dynamical evolution of the jet until the latest epochs (years) post trigger, presently performed only for few events. Complemented by MWL follow up campaigns, they will constrain the physics of external shocks (particle energy distribution, build up magnetic field), the density profile of the external medium. SKA will help to distinguish different GRB and SNe progenitors, and potentially can track the elusive pop-III population at very high redshifts. Radio deep wide-field surveys can access the, yet undetected, population of off-axis 'orphan' afterglows and the emission of the dynamically ejected material during a NS-BH or NS-NS merger: these are among the most promising EM counterpart of high-frequency GW sources. In parallel, the SKA will enable us to directly detect GW at very low GW frequencies (nano-Hz) that pass through our Galaxy, like those emitted by the merger of supermassive black holes, by precisely measuring how the distances to pulsars change.

With their wide field of view and beam-forming capabilities, the SKA and its precursors are the ideal instruments to detect a big number (up to 200 times more than Parkes with SKA1; Macquart et al 2014, PoS AASKA14, 055) of new FRBs and to localise them precisely. This will allow us to perform MWL follow-ups to pinpoint FRB's hosts which, in turn, will enable us to exploit FRBs as cosmological probes.

The Italian community is at the forefront in all the above described fields in the international context. Solid theoretical and observational expertise in transients has been acquired starting with Beppo-SAX through the Swift and Fermi missions. Pilot programs for radio/mm observations are underway with SKA pathfinders/precursors in view of the final SKA. *References…*

2. **Goals** (che il programma si prefigge di raggiungere con specificato ruolo dei partecipanti)

The long term goal of this programme is to maximise the science return from the participation of INAF to SKA and CTA consortia in the following areas: understanding the physics of known classes of transients, discovering and recognising new classes of transients, and exploiting transients as probes of the Universe both locally and at high redshift. This can be achieved through the creation of a well coordinated science network, the development of excellence science activities in the theoretical and observational fields, and solid contributions to the technological challenges (data acquisition, analysis, and management). Communicating to the general public is also a fundamental step to improve the return for INAF.

Many different classes of transients present similar challenges (discovery and localisation), share common physical mechanisms (particle acceleration, compact objects), and display emission in many bands of the EM spectrum, and beyond. For this reason, this project is inherently multi-class, MWL&MM, multi-location, and multi-approach (T: theory, O: observations, D: data analysis and technology; P: public outreach). For each approach, we highlight in the following the main goals, actions, structures involved, and deliverables. In details, we define 12 work packages as follows (the participation of individual members to the WPs is given in the personnel table on pg 9):

T1) Radiation processes. Goals (G): constrain emission mechanisms, activity regions, acceleration processes in outstanding transients. **Actions (A):** Focusing on selected "VIP" events, both recent (such as…) and future, compare observations and models. Some example (suggest your favourite event and question!) **Structures (S):**

T2) A comprehensive model of GRBs. G: obtain a physically complete and consistent model for GRBs, both of the short and long type, on prompt and afterglow timescales, on- and off-axis. This will be relevant for studies of GW progenitors and for the final evolution of core-collapse SNe and super-luminous SNe. **A:** implementation of synchrotron self-absorption emission component and of inverse Compton in the Klein-Nishina regime in the GRB code available at the OABr group. Inclusion of off-axis effects and transition to the non-relativistic phase. **S:** S1-3, S5.

T3) Population models and simulations of radio and TeV emission. G: provide a list of SKA and CTA requirements (reaction time, localisation, energy/frequency range, configuration) for the final design of the detectors, possible strategies for the surveys, and use case revisions. **A:** Based on existing data, improve current population models or develop new ones as needed. Determine detection rates under different assumptions at various frequencies, energies, also to explore synergies with other facilities (e.g. Athena, LSST). Test on precursor data. Complementary to T2, this WP is based on more simplistic models but addresses many more classes (TDEs, SNe, FRBs, binaries of all types). **S:**

T4) Transients as probes. G: Exploit transient sources to constrain parameters of cosmological and fundamental physics importance. **A:** From observed DMs of impulsive radio transients of known distance, determine line of sight electron column density; separate the intrinsic/Galactic contributions through HI and metal absorption; put a strong constraint on the cosmological mass density of intervening Warm-Hot Intergalactic Medium, which is predicted to host the majority of the, yet to be detected, baryons in the local ($z<\sim2$) Universe. From gamma-ray spectral properties of GRBs with known redshift, constrain the EBL at intermediate and high redshift (which also, ultimately, provide information on the column of intervening baryons). From time of arrivals of gamma-ray photons of different energies, study LIV of the speed of light. **S:** S4-6, S9

O1) MWL searches for counterpart localisation. G: Identify the EM counterpart of GW events, determine distance/host galaxy of FRBs, associate new transients. **A:** maintain a channel of information exchange with aLIGO, AdV, and SKA/CTA precursors for GW and other transients follow-up. Design MWL strategies and procedures for search and follow-up of counterparts: study the MWL light curves and spectra of current GW, FRB candidate counterparts, based on the available models of compact stellar mergers and of other explosive potential GW emitters (magnetars, SNe, SGRs); activation of various follow-up approved programs at national and international optical and radio telescopes; real-time detection of GRB contemporary to GW alert with INTEGRAL, and immediate repointing for identification with <1' error box. **S:** S1-2, S7-9

O2) MWL studies exploiting sensitivity (GRBs, SNe, TDE). G: improve knowledge of several transient classes through deeper observations. For many transient sources, the present facilities already provide the possibility to solve many puzzles, as the frequency of the relativistic SNe, the SNe rate in starburst galaxies (often hidden behind dust), physics of accretion on supermassive BH after TDE, the quenched activity states in binary, etc. **A:** selection of new, well localised MWL transients as SNe (also to search for orphan GRBs), TDE, GRBs, novae for follow up with sensitive radio arrays (JVLA, MeerKAT, ASKAP). Monitoring of binaries in different states, with single dish and interferometers. **S:**

O3) Imaging at very high angular resolution. G: Obtain direct imaging of ejecta in various classes of sources, constrain structural and positional evolution. **A:** Data analysis, interpretation, and publication of already available VLBI datasets on the first gamma-ray nova V407 Cyg, the XRB Cyg X-3 during 2016 giant flare, and two recent GRBs. Derive implications for circumstellar medium, energy density, GRB viewing angles. Promptly react to new transients exploiting real time correlation on flexible arrays based on Italian radio telescopes. **S:** S4-6

O4) Gamma-ray observations. G: the number of transient sources observed at (very) high energy gamma rays is relatively low. This WP aims at a characterisation of a few outstanding objects detected in these bands with the present facilities. **A:** observations of binaries, novae, GRBs, jetted TDEs, with MAGIC, Fermi, and AGILE, and for truly outstanding outbursts, ASTRI. Study of the temporal evolution and of the spectral shape. **S:**

D1) Test capabilities of national facilities for transient discovery towards SKA. G: develop expertise in impulsive radio transient detections, discover new objects. **A:** develop analysis tools (software, firmware, backends) for possible exploitation of national instruments as radio transient discovery facilities: Sardinia Radio Telescope, refurbished sections of the Northern Cross, Sardinia Array Demonstrator. Initial tests on known pulsars with suitable characteristics and repeating FRBs. Blind searches in transit mode. Possible spin-off for discovery and characterisation of near earth asteroids. **S:** S4, S6, S10

D2 - Real-time analysis techniques & decision trees. G: Contribute to set strategies for CTA/SKA reaction to transients and target prioritisation. **A:** Development of analysis techniques for the serendipitous discovery and/or identification during MWL/MM campaigns of gamma-ray transients at different timescales (minutes to days) for the Real-Time Analysis of CTA, in particular with a focus on GW EM counterpart. Definition of decision trees for the management of science alerts based on figure of merit (FoM) algorithm. Test by means of both the CTA and SKA precursors. Develop visualisation techniques of data analysed in real-time and at different timescale in the full Field of View of CTA (taking into account the different sub-arrays). **S:** S1-2

D3 - "Small big data": databases, archives, MWL searches and coordination. G: Develop new methods to extract and handle information from huge time series and data sets. **A: tbd S:** S1, S9

P - Public outreach. G: Present CTA/SKA projects and transient phenomena to the general public, pointing out Italy's role and creating emotional involvement. **A:** set up one exhibit about SKA/CTA and Italy's role; one documentary about the people involved in the SKA/CTA; three educational hands-on activities (for details, see cost breakdown section). Collaboration with SKA/CTA outreach and education offices and INAF communication office. Local activities. **S:** S2,4,5,10

Deliverables for the T and O WP are mainly science papers in peer-reviewed international journals (at least two per WP per year, for a total of >32) and oral and poster presentations in international conferences. The D packages have a more technological and data oriented focus, aimed at preparing software/hardware resources to be exploited in the mid-long term: deliverables in this WP are pipelines, software, observational tests (at least one per facility), technical reports and communications to international conferences in the technological/instrumental field. The P WP will deliver outreach media as outlined in the cost breakdown section.

3. **Impegno di personale** di ruolo dedicato al programma (in FTE) distinto per qualifica e ruolo all'interno del programma e suddiviso per strutture di ricerca (per gli associati vale la struttura di associatura)

capacità del progetto di aumentare il coinvolgimento at large della comunità

- completare con elenco partecipanti definitivo
- riportare totale FTE INAF su totale
- riportare totale FTE TI rispetto nuovi FTE richiesti (>1:5)
- riportare check 100k€:2FTE
- riportare presenza in WG SKA/CTA

IRA

Name	Qualification	WP	FTE
Marcello Giroletti	R		0.5, 0.5
…			

IASF-Bo

Name	Qualification	WP	FTE
…	…		
…			

IAPS

Name	Qualification	WP	FTE
…			

IASF-Mi

Name	Qualification	WP	FTE
…			

4. **Project cost breakdown** [Costi del programma suddivisi per macro-voci (quota spese generali, investimento, consumo, calcolo, missioni, personale, pubblicazioni)]

Table n: Cost breakdown

Reason	**Requested funds (k€)**
Overhead	120
Outreach	40
Hired personnel	490
Travel	150
Total	800

In Table n, we report the share of costs. The largest fraction of requested funds is for the acquisition of new personnel. This is driven by two main reasons: on one hand, it is vital to support junior researchers from the early stages of their career in the field of SKA and CTA studies, as they will eventually be the prime users of these facilities. Moreover, although our group is large and diversified, most of our goals require the commitment that only a person devoting 100% of its time to the corresponding action can warrant. We will encourage interaction among all the members of the team and the newly acquired unit, which will benefit both parties. Moreover, for each unit of acquired personnel, the work will not only be tied to a single reference structure, to which the post-doc will be affiliated and where they will spend most time. Since all topics are of interest for more than one structure and fostering the link among various location is one of our goals, we also indicate for each position also the other structures that will be collaborating with the post-doc on the same theme. We will also divide the resources for travel so that the structures who do not acquire new personnel will have the possibility to have more mobility - to encourage interaction and maximise the return of the work. In one case, we will offer a senior position (RTD, 52.5 k€/yr) to acquire at least one unit of personnel with an advanced formation; in all the other cases, we will offer standard INAF salaries (ADR, 35 k€/yr), which should still attract brilliant junior researchers, in particular for the longer positions (three 2-yr and two 1.5-yr contracts). Comparatively shorter positions (1-yr) will be offered for two more focused projects on development of analysis techniques in gamma rays and radio, which might be then followed-up with local funds.

We also intend to carry out research activities for a total of 40 k€ (5% of the total budget). In details, we estimate the following costs and activities:

- an exhibition presenting SKA and CTA, with panels (Italian and English) showing: what SKA and CTA are, their position and configuration; what radio and high energy waves are, what they can reveal about the objects emitting them; how the two instruments can be jointly used in order to answer to some astrophysical big questions; how radio and gamma images are produced from the collected data; what the role of Italy has been, is and will be. Each panel will have a digital frame showing videos about the subjects. The exhibition will be completed by the accompaniment of a music, the “sonification” of radio waves and gamma rays obtained by actual observations of transient phenomena, arranged in order to produce a symphony. An exhibit at the end of the exhibition path will show how that sounds were produced and explain that, since the observed information are not visible, any “translation” into sensible inputs can work. The use of digital frames in the exhibition’s panels will allow a great feasibility in order to include brand new discoveries or other currently unexpected contents related to this PRIN project. Costs: panels: 10k€, musical accompaniment: 5 k€, final exhibit: 5 K€

- 1 documentary in the style of “Quelli che la Fisica” (https://www.youtube.com/watch?v=Y0L8rfYz0WI) about the people involved in SKA and CTA, their work and expectations and about the social aspects related to the Italian role in the CTA and SKA projects. Cost 10 k€
- 3 educational hands-on activities for different targets (involving students from all school grade levels) i) showing the global coverage of the SKA and CTA observing facilities scaled to accessible dimensions, made up of simple materials, easy to build and to reproduce; ii) using music and sounds in order to explain what a transient phenomenon is in term of duration related to the typical timescales of the Universe, using music and sounds and engaging in the research of possible explanations of the nature of these fascinating events. [approx. cost 6 kEuro for the design and production of the 2 prototypes and their low cost reproducible version; 4 kEuro for the production of roughly educational kits to be used in the involved structures].

All products will be designed in order to easily adapt to additional modular contents and to be easily adjustable within other contexts. All product will be available to be used within INAF Outreach and Educational activities at national and international level.

Personnel to be hired						
Topic	**Type**	**Duration (months)**	**Cost (k€)**	**Reference structure**	**WP**	**Other structures**
MWL search and characterisation of unidentified high energy transients and GW counterparts	RTD	24	105	IASF-BO	O1	
New physical insights on GRBs and TDEs in the SKA and CTA era	ADR	24	70	OABr	T2, T3	
The unexplored extremes of the electromagnetic emission from SNe: from gamma rays to radio	ADR	24	70	OAPd	O2	
MWL analysis and data mining of transient events toward the CTA and SKA era	ADR	24	70	OARm	D2, D3	
Accretion- and ejection-powered Galactic transients and development of target prioritisation strategies	ADR	18	52.5	IAPS	T1, O4	
Transient events follow ups and SKA/CTA-Athena synergy	ADR	18	52.5	IAPS	O1	
Studying transients through real time imaging at the highest angular resolution with VLBI	ADR	12	35	IRA	O3, D1	
Development of analysis techniques for high-energy transients identification and follow-up in the MM and MWL context	ADR	12	35	IASF-BO	D2	

Notes: RTD = Ricercatore a Tempo Determinato; ADR = Assegno di Ricerca

5. Resources from INAF research structures

5.1 **Financial resources**

IAPS 6 months co-funding for "Transient events follow ups and SKA/CTA-Athena synergy" position.

5.2 Instrumental resources

High energy

Our group has been a major contributor to the design, development, and installation of the ASTRI dual-mirror small size telescope end-to-end prototype (**ASTRI SST-2M**). ASTRI SST-2M has been installed at the Serra La Nave observing station (INAF/OA-Catania, Mt. Etna) and it is currently performing commissioning and engineering tests. From Spring 2017, it will start acquiring scientific data on the Crab nebula and on a few variable sources, such Mrk 421 and Mrk 501. The ASTRI SST-2M prototype is an important observing facility for INAF, the VHE community and our research group. Thanks to the end-to-end approach, it will allow scientists and technicians in our team to become acquainted with one of the CTA telescopes, its data collection and analysis.

MAGIC as precursor.

Membership in **Fermi & AGILE,** possibility of prompt reaction to gamma-ray transients (…)

Radio

IRA has upgraded a section of the **Northern Cross** (…)

OACg participates in the activities of **Trapum** with MeerKAT (…)

Mc, Nt, Sr, and their combination as VLBI in EVN and ad hoc small and flexible networks - with DiFX correlator installed and run in Bologna

MWL

Our group (through OABr) is deeply involved from the design to the in-orbit operations in the **Swift** mission, actively participating to the scientific management of the mission. In the 11 years since launch, Swift's scientific program has expanded significantly beyond the realm of GRBs. Swift has become an unequaled Target of Opportunity (ToO) machine for the astronomical community. The rate of approved targets is now 4 per day, far exceeding any other mission. Thanks to its prompt reaction time, Swift provides the best suite of instruments, from optical/UV to hard X-rays, to follow-up and study newly discovered sources at other wavelengths.

IAPS, IASF-Mi, and IASF-Bo have a significant participation in **INTEGRAL**, the wide field satellite observing the sky in hard X-rays/soft gamma rays since 2002. In 2017 and 2018, our group is leading (PI A. Bazzano) an INTEGRAL program to scan the galactic plane, for 2 Msec every year, and a ToO proposal for TDEs (PI F. Panessa).

This project includes a large fraction of the Italian community (including the Italian PI) involved in the Imaging X-ray Polarimetry Explorer (**IXPE**) mission recently approved by NASA for a launch in 2020. Among the key science goals of the mission, there is the study of the boundary conditions of the jet launching mechanisms, including transients such as binaries and TDEs.

5.3 Computing resources

IAPS has a BLADE architecture (UV 2000 SGI) for the processing of INTEGRAL data, based on high speed storage and parallelisation of the data processing. The architecture uses both temporary RAMdisks and NVMe. At present, the BLADE AVES2 consists of 160 CPUs, 1TB available RAM, Numalink 6 connectivity and 2 x 48 TB Qsan F600Q-D316 SSD data storage units. The facility will be available for use within this project, if approved.

IRA hosts and operates the software correlator for VLBI observations based on the Italian stations. It is currently composed of 4 "tanks" providing real-time acquisition capabilities for up to 5 stations transferring data at 1 Gbps rate, with a storage of 150 TB, and 24 cores. Flexbuff storage is being installed at the Mc and Nt stations, providing capability to simultaneously record and transmit voltage data.

5.4 Risorse osservative/collaborazioni/tempo garantito

OAPd and OACn are members of **ePESSTO** (the continuation of PESSTO, Public ESO Spectroscopic Survey of Transient Objects; in particular S. Benetti is in the PESSTO Science Board), using the ESO New Technology Telescope and the EFOSC2 (optical) and SOFI (NIR) spectrographs. It is one of two currently running public spectroscopic surveys at ESO. OAPd personnel is also involved in **NUTS** (the NOT Unbiased Transient Survey). The membership in these two international collaborations offers the possibility of a prioritary access state of the art facilities of great relevance for many topics in our research project, such as SNe, TDEs, GRBs, and binaries.

Concerning the specific classes of transient sources related to this research project, our team is leading (at the level of PIship) many programs for space and ground-based follow-up of GRB, FRB and GW. In more detail:

GRB follow-up

- XMM-Newton (PI: P. D'Avanzo): 70 ks/year
- REM (PI: A. Melandri, OAB), 100 hours/semester
- TNG (PI: V. D'Elia, OAR), 10 hours/semester
- LBT (PI: P. D'Avanzo, OAB and A. Rossi, IASFBo): 6+16 hours/year
- ESO-VLT: (PI: P. D'Avanzo): 12 hours/semester
- ESO-VLT (PI: E. Pian, IASFBo): 6 hours/semester (GRB-SN)

FRB follow-up

- REM (PI: S. Campana, OAB): 45 hours/semester

GW follow-up

- REM (PI: S. Campana, OAB): 10 hours/semester
- NOT (PI: E. Pian, IASFBo): 10 hours/semester
- ESO-VST (PI: E. Cappellaro, OAPd e A. Grado, OACn): 30+30 hours/semester
- ESO-VLT (PI: E. Pian, IASFBo): 12 hours/semester
- TNG (PI: S. Piranomonte, OAR): 40 hours/semester
- LBT (PI: E. Palazzi, IASFBo): 16 hours/year
- Campo Imperatore Schmidt (wide field) +AZT24 (NIR)(PI: E. Brocato, OAR): INAF/OAR-telescope piority for GW-ToO
- Asiago Schmidt + 1.82m (PI.: L. Tomasella, OAPd): INAF/OAPd telescope high priority for GW-ToO
- SRT (PI: A. Possenti, OACg): 75 hours/semester
- ATCA (PI: A. Possenti): 120 hours/semester

Many members of our team are also involved in the ESO-VLT X-shooter program devoted to measure GRB redshifts (PI: J. Fynbo, DK) and in the NOT, TNG and ESO-VLT programs for the follow-up of FRB (PI; D. Malesani, DK). Many of the above programs have a long term status or are likely to be extendend for the entire duration of the present research project.

VLBI proposals

Dichiarazione datata e firmata di accettazione da parte del Direttore della Struttura INAF di affluenza del CSN e nulla osta da parte dei direttori di struttura

Assenso del CSN ecc ecc

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