Discovery, localisation, and physics of transient sources towards the SKA and CTA era

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 (1) the discovery of a $>5.1\sigma$ transient GW signal by a-LIGO, with a plethora of follow-up interpretative and multi-wavelength observational papers; (2) the debate about the first possible extragalactic localisation of a FRB (Keane et al. 2016, Williams & Berger 2016), as well as the discovery and identification of the first repeating FRB (Spitler et al. 2016, Chatterjee et al. 2017); (3) the appearance of new theory- and observation-based population studies of TDE rates (Stone & Metzger 2016, Holoien et al. 2016). 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 black hole mergers and their formation from massive stars in low-metallicity environments, the average cosmic density of ionised baryons in the intergalactic medium, the supermassive black hole 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 (Fender et al. 2014). Gamma rays have the complementary advantage of directly tracing the highest energy particles and of probing the extragalactic background light (EBL). 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 to dramatically increase the number of detected transients and the level of details in which they could be studied. Indeed,

List of acronyms

GW	gravitational waves	WD	white dwarf
GRB	gamma ray burst	MWL	multi-wavelength
FRB	fast radio burst	EM	electromagnetic
XRB	X-ray binary	aLIGO	Advanced Laser Interferometers GW Observatory
SN	supernova	AdV	Advanced Virgo
BH	black hole	CTA	Cherenkov Telescope Array
NS	neutron star	SKA	Square Kilometre Array

"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 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 $>10^3$ gamma-ray bursts (GRB), we know a greater deal about them in comparison to the dozen or so of FRBs, for which it is still debated whether they are of galactic or extragalactic origin. However, there are 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 GRB afterglows does also depend on models developed for known GRBs seen on-axis, localising a FRB or a GW event have many steps necessarily in common; most transients are inherently MWL emitters. Indeed, several scientists in our team are active in more than one of these fields and members of both SKA and CTA working groups. 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 era of gravitational astronomy era, with the first detection of **GW** achieved by the aLIGO and AdV collaboration [1]. 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 [2]. 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 well known EM events as short GRBs [3]. 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.

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 (…). 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 … This has tremendous implications for the progenitor and for probing the cosmic density of ionised baryons. Many open questions remain, such as *ci sono due classi? dove si trovano i non-repating? quali sono i progenitori? quali sono le implicazioni su mezzo, cosmologia, ecc? emettono ad alte energie (vedi swift)? And note the very high number *per sky* expected per day.*

GW progenitors can be binary systems of compact objects, which are also thought to be the progenitors of the short-timescale flavour of **GRB**. 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. Increasing observational evidences 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 the MeV to the optical bands 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**. The search for and the study of SNe explosions 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 and of their recent history of mass loss. However, radio detections of both GRBs and SNe are rare (<30%), and neither class has been secured a detection above 100 GeV so far.

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. 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 (Chenet al. 2016) 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, microquasars). Many of these sources have shown surprises: symbiotic and classical novae have been revealed as a new class of gamma-ray emitters by Fermi, 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 emission region (refs). Millisecond pulsar binaries accreting at very low-rates have recently found to surprisingly emit at radio and GeV energies and transiting from a disc and disc-free states on timescales of months-yrs (); analogously, the unique WD binary AE Aqr has shown bright radio flares and a puzzling high energy behaviour, with both detections and upper limits (); 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 the understanding the accretion/ejection coupling on much shorter timescales than 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 understood, mechanism is in place that accelerates particles up 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 LIGO/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 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 collimating 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 UHCRs and neutrinos and will use GRBs to constrain the EBL at intermediate and high redshifts and to study the violation of the Lorentz invariance of the speed of light through the expected energy dependence of photon arrival times. 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 wide-field-deep surveys can access the, yet undetected, population of off-axis afterglows ("orphan afterglows") and the emission produced by the dynamically ejected material during a NS-BH or NS-NS merger: these are among the most promising EM counterpart of GW sources. In parallel, the SKA will enable to directly detect gravitational waves at very low GW frequencies (nano-Hz) that pass through our Galaxy, as the ones emitted by the merger of supermassive black holes, by precisely measuring how the distances to pulsars change.

Many more FRBs, already with precursors, and imaging potential for binaries…

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…*

Goals (che il programma si prefigge di raggiungere con specificato ruolo dei partecipanti, max 2pg)

The long term goal of this programme is to ensure that INAF will be ready to exploit the wealth of data from SKA and CTA 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. Many different classes of transients present similar challenges (discovering and localising them), share common physical mechanisms ( ), and display emission in many bands of the EM spectrum, and beyond. For this reason, this project is inherently multi-class, multi-wavelength, multi-location, and multi-approach (observational, theoretical, and numerical).

Therefore, many different strategies can be proposed to maximise the efficiency of our actions… Some actions are listed below - need to integrate them with other input and group them in a logical WP scheme.

- revise detection rates for CTA and SKA of GRBs and TDEs, based on advanced population models developed by the OAB group. Consider both the pointed and off-axis populations. Compute emission at different frequencies to exploit the synergies with other facilities (e.g. Athena, LSST etc.).
- implementation of synchrotron self-absorption emission component and of inverse Compton in the Klein-Nishina regime in the GRB code available at the OAB group. Inclusion of off-axis effects and transition to the non-relativistic phase for the development of the scientific case of orphan afterglows (in concert with GW interferometers) and of radio calorimetry.
- development of pilot observing programs to test the best strategies for the multi wavelength observations of GRBs and TDEs from the radio to the TeV range. This task will complement the present activity at the OAB devoted to the follow up of transients in the optical band and soft/hard X-rays. The synergy with forthcoming optical surveys, e.g. LSST, will be crucial (especially for TDE that will provide a high detection rate).
- study of specific scientific cases (e.g. detection of Pop-III progenitors of GRBs, disk formation in TDE) for SKA and CTA aimed at providing a list of requirements for the final design of the detectors and the possible strategy for the surveys.
- Target prioritisation based on Figure of Merit: CTA and SKA are multi-object observatories, with target lists coming from the respective consortia and the whole community through guest observer programs, including ToO on transient sources. They need observing priorities based on object class and scientific opportunities. Drawing from our extensive experience collected with fast/automatic-response observatories, develop a decision tree based on figure of merit (FoM) algorithms, to quicken and possibly automate target selection during the lifetime of these observatories. Investigate a FoM methodology that can be applied to all CTA and SKA scientific Use Cases currently being developed. Test by means of both the CTA and SKA precursors.
- Simulations of radio and TeV expected emissions in the assumption of leptonic/hadronic models. Example of Cygnus X-3, where theoretical models found out that both hadronic and leptonic scenarios can account for the observed gamma-ray activity. Hadronic models are based on gamma-ray emission from the decay of $\pi 0$ produced by strong interactions between accelerated hadrons from the jet and nuclei from the companion wind. Leptonic models are based from IC scatterings between relativistic electron/positrons from the jet and soft photons from the companion star. A full spectrum simulation (from radio to TeV energies), in which (self)absorption is taken into account, is a fundamental ingredient to properly understand the correlation between radio and gamma-ray emission (the same population of electrons radiates in

the radio band via synchrotron emission, and in gamma-rays via IC processes), and to possibly disentangle between hadronic and leptonic processes in these binary systems. [TEMA SIMILE PER ALTRE CLASSI]

- exploit existing (EVN, Italian VLBI) and new real time VLBI datasets for the structural evolution and localisation of transients (eg V407 Cyg, Cyg X-3, future binary flares/state transitions, GRBs, FRB - *citare dataset disponibili in resources*)
- develop analysis tools to explore possibility to discover FRBs with national resources such as Northern Cross or SAD, by means of tests on pulsars or known repeating FRBs
- 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 Gravitational Waves EM counterpart.
- definition of decision trees for the management of science alerts (a significant detection of a transient source that requires a follow-up strategy) generated by CTA & development of a database of candidate counterparts for the selection of the best observing strategy,
- development visualisation techniques of the data analysed in real-time and at different timescale in the full Field of View of CTA (taking into account the different sub-arrays)
- real-time detection of GRB contemporary to the LVC alert with INTEGRAL, or upper limit set, as already done for the first two events. Distribution in real time of the GRB trigger and profile, while detected from IBAS pipeline. Immediate re-pointing of the satellite to look for the X and Gamma-Ray afterglow. Identification with <1' error box of the emission cosmic source and its identification. Search of high-energy sources related to GW alerts.
- development of new procedures for the optimisation of INTEGRAL observations searching for EM counterpart of GW and high energy neutrinos (prompt emission and ToO)
- study the frequency of the relativistic SNe - the observation and analysis of their properties will allow us to outline the observational strategy in the CTA/SKA era.
- study the physics of the ejecta and the distribution and geometry of CSM - their interaction in the radio and in high-energy domains are crucial for the characterisation of SN progenitors and the mechanisms of the mass loss.
- study hidden SNe behind dust for the estimation of the SNe rate in starburst galaxies - the principal goal is the optimisation of the observational techniques in the SKA era, with the aim of obtaining a fast photometric classification of the discovered transients using the radio light curve
- Total energy budget and SED of SN explosions, up the the unexplored extremes of the electromagnetic spectrum - using multi-frequency monitoring for a selection of targets.

Possible grouping:

Key area #1: discovery and localisation - The identification of transients detected by wide-field facilities is a key problem. This is certainly the case for GW events, for which a MWL network is in place, and recent experience has also shown the importance of the matter for FRBs. This is of great importance both for the understanding of these classes of transient events, as well as for developing expertise and tools that will become fundamental once the SKA and CTA start discovering new transients, possibly of unknown and unpredicted type. [Localisation - è fondamentale per GW e per FRB. ad esempio chiarire se FRB sono galattici o extragalattici (*121102 è l'unico ed è repeating quindi non è la fine della storia*). deve per forza di cose basarsi su un forte coordinamento MWL. Se funziona può essere vincente anche per future nuove classi di eventi.]
Key area #2: the physics of known classes of transients
Key area #3: data analysis technique and interpretation

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)

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
…			

- 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

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

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.

Description of outreach activities and costs (…)

Table n: Cost breakdown

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

Personnel to be hired

Topic	Type	Duration (months)	Cost (k€)	Reference structure	Other structures
MWL search and characterisation of unidentified high energy transients and GW counterparts	RTD	24	105	IASF-BO	
	ADR	24	70	OABrera	
The unexplored extremes of the electromagnetic emission from SNe: from gamma rays to radio	ADR	24	70	OAPadova	
	ADR	24	70	OARoma	

Topic	Type	Duration (months)	Cost (k€)	Reference structure	Other structures
	ADR	18	52.5	IAPS	
	ADR	18	52.5	IAPS	
	ADR	12	35	IRA	
Development of analysis techniques for high-energy transients identification and follow-up in the MM and MWL context	ADR	12	35	IASF-BO	

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

Instrumental resources from INAF research structures

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.

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 (…)

MWL

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.

The two telescopes (Copernico 1.82m and Schmidt) at the **Asiago Observatory** (OAPd) are available through a guaranteed large program for the follow up of transients (up to 5 nights per month until January 2018, likely to be extended for the entire duration of the present research project).

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).

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