START PAGE

MARIE SKŁODOWSKA-CURIE ACTIONS

Individual Fellowships (IF)
Call: H2020-MSCA-IF-2015

PART B

“Radio-Optical Transients”

This proposal is to be evaluated as:

[Standard EF]

Table of Contents

List of Participants

Participants	Legal Entity Short Name	Academic	Non-academ	Country	Dept./Div./Lab	Supervisor
THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF OXFORD	UOXF	✓		United Kingdom	Department of Physics	Robert Fender

Unveiling the Radio Transient Universe
(A Unique Synthesis of Joint Radio-Optical Surveys and Artificial Intelligence)

1 Excellence

1.1 Quality, innovative aspects, and credibility of the research

1.1.1 Introduction, state-of-the-art, objectives and overview of the action

While synoptic survey telescopes at optical, X-ray, and γ-ray wavelengths (e.g. Gehrels et al. 2009, Michelson et al. 2010, Kasliwal 2012) have revealed a rich discovery phase space of astrophysical transient phenomena — multitude of classes of supernovae, long-, short-, and ultra-long-gamma-ray bursts, tidal disruption events, stellar flares, novae, magnetar outbursts, and actively accreting black holes with jets — that have transformed astronomy in a fundamental way, a similar yield is still awaited in the radio.

Radio transients are both the sites and signatures of the most extreme phenomena in our Universe. They provide a unique perspective on obscured, unbeamed (afterglow), and magnetically-driven processes not readily accessible through optical, X-rays, and γ-rays. Radio transient phenomena give key insights on the formation of astrophysical jets, the physical conditions of the circum-burst environment, the interaction between fast outflows and ambient media, the calorimetry for the kinetic feedback, and serve as test beds for theoretical models of charged-particle acceleration. Moreover, radio transients probe extreme astrophysical conditions of temperature, pressure, density, mass, and magnetic field intensity, which are impossible to currently reproduce in terrestrial laboratories. The exploration and study of radio transients is therefore extremely important.

Despite this advantage offered by the study of radio transients, the development of radio transient astronomy has been impeded by several factors: 1) the lack of dedicated radio telescopes to carry out multi-epoch wide-field surveys, 2) the inability to carry out near-real-time radio data processing, rapid multi-wavelength follow-up, and robust transient classification (Thyagarajan et al. 2011, Bannister et al. 2011), 3) contamination by false positives (e.g. Bower et al. 2007, Kuniyoshi 2009, Frail et al. 2012), 4) the lack of dedicated radio follow up facilities for continuous monitoring of radio transients, and 5) the current incapacity to efficiently deal with large volumes of data from new radio interferometers. As a result, our knowledge of radio transients is mainly restricted to what is revealed by follow up observations of a subset of astrophysical transients discovered at optical, X-ray, and γ-ray wavelengths.

With these issues in view, **I put forth an ambitious and comprehensive work plan in this proposal to substantially advance the field of radio transient astronomy. The proposal is premised on the three-fold strategy: "*Discover–Learn–Communicate*".** The *Discover* aspect utilises unique observational techniques, such as joint radio-optical surveys, to discover new transients, thus obtaining their occurrence rates and preliminary classifications, and opening avenues for further study. The *Learn* aspect studies the radio transients in detail through their light curves, and uses this information along with artificial intelligence to "learn" to automatically classify the transient phenomena. The *Communication* aspect deals with the efficient dissemination of the research results, and public engagement.

As part of my Ph.D., I have worked extensively on radio and optical transient surveys with the Jansky VLA (JVLA) and the Palomar Transient Factory (PTF), and this proposal is a logical extension of that work. The proposed host institution, the University of Oxford, has recently joined the collaboration of powerful radio and optical telescope facilities, viz. MeerKAT, MeerLICHT, the Square Kilometer Array (SKA), and the Large Synoptic Survey Telescope (LSST). It also has direct access to a very successful robotic radio monitoring facility, the Arcminute Microkelvin Imager (AMI). Moreover, the proposed supervisor, Robert Fender, is a world-leader in radio and X-ray transients, and the co-principal investigator (co-PI) of transient search programs planned for MeerKAT and SKA. **As a Marie Curie Fellow, I will therefore be in a unique position to exploit the enormous data from these new and power-**

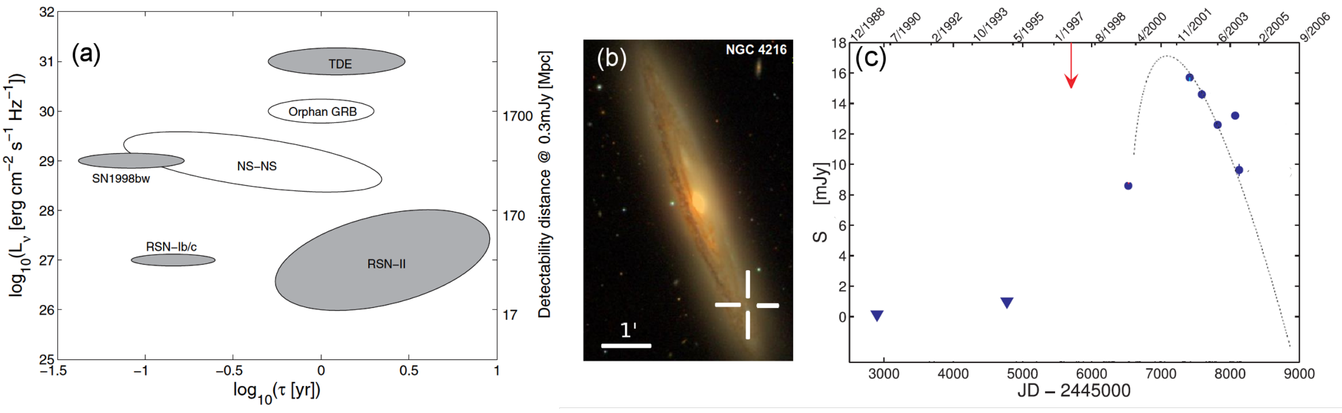

Figure 1: *Extragalactic explosions will be the focus of the proposed joint radio-optical surveys. (a) The luminosity-timescale phase space of these transients from Frail et al. (2012). (b) The optical image of a nearby galaxy, NGC 4216, with the location of the core-collapse supernova discovered by Gal-Yam et al. (2006) marked. (c) The 1.4 GHz light curve of the Gal-Yam et al. (2006) supernova. The red arrow marks the estimated explosion date.*

ful telescopes. I will develop state-of-the-art data processing software for rapid transient search, and implement it on these telescopes for discovering new transients. Through my existing collaborations, JVLA and PTF will also serve as survey and follow up facilities. I will also coordinate radio follow up observations with the AMI telescope. Additionally, I plan to use the data from newly-discovered transients along with archival data to innovate a fully-automated radio transient classification system via artificial intelligence techniques. The data generated by this work will serve as a rich resource for the astronomical community, and the techniques developed will be fully transferable to other telescopes. Finally, the proposed work will greatly benefit the researcher and the host institution by means of fostering new collaborations, improving the big data know-how, and enhancing the career prospects.

1.1.2 Research methodology and approach

The objectives described in the previous subsection will be achieved through three distinct, but related, projects: 1) Discover and study radio transients via joint radio-optical surveys and multiwavelength follow up, 2) Rapid radio follow up and monitoring of transients discovered at radio, optical, X-ray, and γ-ray wavelengths with the AMI telescope, 3) Automated radio transient search and classification using artificial intelligence. These approach and methodology for each project is described below in detail. The first project belongs the *Discover* category of the proposal and the other two belong to the *Learn* category. The *Communication* aspect of the proposal is associated with all three projects, and will be described in section 3 (Impact) of this proposal.

1.1.2.1 Incoherent transient phenomena via joint radio-optical surveys and rapid multiwavelength follow up

Incoherent or slow transients, such as radio supernovae, novae, and stellar flares, are powered by synchrotron or thermal emission mechanisms, have timescales longer than one second, and are discovered via radio imaging techniques. Essentially all explosive events in astrophysics are associated with incoherent synchrotron emission, resulting from ejections at velocities in excess of the local sound speed that compress ambient magnetic fields and accelerate particles. My focus in this proposal be on the discovery and detailed study of extragalactic explosions (Figure 1), phenomena that largely motivate transient surveys in the optical, X-rays, and γ-rays. I thus propose to study core-collapse supernovae, orphan afterglows of gamma-ray bursts, binary neutron star merger events, and tidal disruption events in detail.

Joint radio-optical surveys with JVLA-PTF and MeerKAT-MeerLICHT. Joint radio-optical surveys have a number of advantages over radio-only surveys to study transients, in that they offer: 1) a more complete census of transients with the highly dust-obscured transients being captured by the radio emission, and others by optical and radio emission, 2) a better means of rapidly vetting and classifying transients via light curves at two very distinct frequencies, and 3) simultaneous studies of accretion disks and jets for accretion/jet-powered transients, of thermal/non-thermal emission in flare stars, and of correlated emission in radio and optical.

The Palomar Transient Factory (PTF) is a highly successful, wide-field, automated optical survey that has discovered more than 2500 supernovae, and 100s of other classes of transients, since 2009. By mid-2017, PTF will be upgraded to the Zwicky Transient Facility (ZTF), a new time-domain survey having a greatly increased field of view of 47 deg^2. The Jansky VLA, a newly-upgraded radio telescope facility, is the first operational interferometer with the sensitivity and survey speed to routinely detect the extragalactic explosive population with modest time allocation. A pilot radio-optical survey over 50 deg^2 of the Stripe 82 region of the sky has already been carried out with the JVLA and PTF (Mooley et al. 2015). Over the three months of high-cadence PTF search, eight spectroscopically-confirmed supernovae were discovered. Additionally, three stellar flares and several active galactic nuclei (AGN) were detected in the radio, which had optical variable counterparts in PTF. The conclusion of this successful pilot study was that shallow optical surveys should be coupled with deep radio surveys or vice versa, or both the surveys should to be deep (μJy-level sensitivity), in order to recover the majority of transients at radio and optical wavelengths.

MeerKAT-MeerLICHT is a unique and powerful radio-optical experiment which will commence full science operations in mid-2017. MeerKAT is a radio facility under construction in South Africa and a pathfinder for the SKA. It will have a 1 deg^2 field of view, and will initially operate between 0.9 to 1.67 GHz, but eventually between 0.6 to 15 GHz. The combination of a wide field of view, wide frequency coverage, and excellent sensitivity makes MeerKAT the most powerful southern hemisphere telescope for transient studies. The scientific focus of MeerLICHT, a fully-robotic 60-cm telescope also with a 1 deg^2 field of view, is to obtain optical data simultaneous with MeerKAT on astrophysical transients.

Guaranteed telescope time: Robert Fender, the proposed supervisor, is the co-PI of ThunderKAT, a transient survey programme that has been awarded 3000 hours of dedicated time over the first 5 years of MeerKAT operations. Moreover, transient search in all of the MeerKAT survey data has recently been approved. The MeerKAT-MeerLICHT commensal observations, amounting to nearly 5000 hours, are expected to yield an abundance of transient discoveries. Additionally, 5600 hours of observing time with the JVLA has recently been approved as part of the VLA Sky Survey (VLASS[1]), a community-lead multi-epoch survey of the northern sky starting in early 2016 and running for several years. VLASS is expected to find tens of new cosmic explosions, and coordinated optical observations with PTF/ZTF have been planned.

Radio transient detection rates. There are reasonable estimates of radio transient detection rates available from previous studies (Frail et al. 2012, Mooley et al. 2015). Considering the sensitivities and fields of view of the radio telescopes, a timescale of a 1–few years for the evolution of radio emission from cosmic explosions, and assuming 50 hours of dedicated transient survey time per week, we expect to find 1–2 new explosions per month with MeerKAT and 10–15 explosive transients per year in the VLASS. This will make a significant impact on radio transient astronomy, given that, to date, only a handful of cosmic explosions have been discovered in radio transient surveys.

Proposed work. I will develop a state-of-the-art data processing software pipeline for rapid radio transient search. The basic software infrastructure for achieving this goal has already been built as part of my Ph.D. thesis. The data processing pipeline will be implemented for JVLA and MeerKAT for discovering new transients. I will implement a comprehensive multiwavelength follow up programme through existing collaborations with the SWIFT X-ray observatory, the Keck and Palomar optical observatories, and

[1] https://safe.nrao.edu/wiki/bin/view/JVLA/VLASS

the AMI radio telescope. In this way, I will fully exploit the discovery of transients in joint radio-optical surveys, and study the extragalactic explosions in detail.

1.1.2.2 Robotic radio follow up with AMI

Since 2013, an extremely successful programme has been running on the AMI Large Array telescope (located in Cambridge, UK), in which the telescope is robotically overriden on the basis of triggers generated automatically by NASA's Swift space mission (ALARRM mode). With no human intervention, for a well-positioned source, AMI can be on-target within minutes (Staley et al. 2013), delivering a 2-hour observation centered at 16 GHz. Following each ALARRM trigger, each source continues to be monitored regularly via manual scheduling in order to search for emerging radio emission. This programme has, to date, followed up well over 150 transient events, delivering exciting science such as:

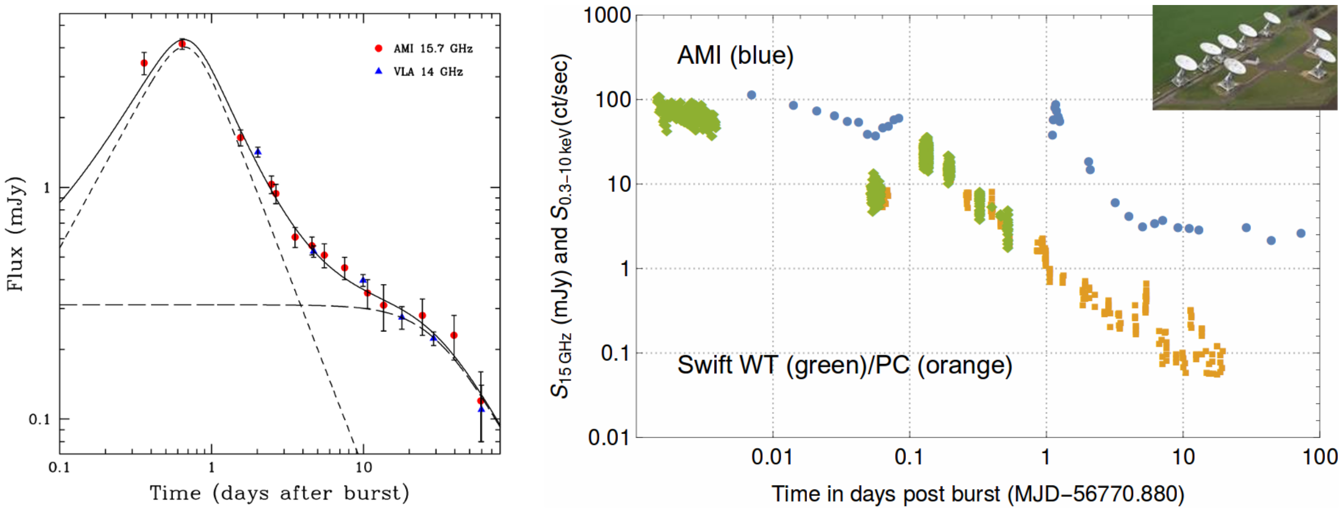

Figure 2: *Exciting transient science delivered by the robotic radio telescope, AMI. Left: The first detection of a reverse shock peak in GRB 130427A. Right: A very fast radio flare associated with a gamma-ray superflare from DG CVn.*

- The first detection of a reverse shock peak in the jets of GRBs (Anderson et al. 2014; Figure 2, left). ALARRM triggered on GRB 130427A 8 hours post-burst when it had risen above the horizon yielding one of the earliest radio detections of a GRB and demonstrated a clear rise in flux less than one day after the γ- ray trigger followed by a rapid decline. At later times (about 3.2 d post-burst), the rate of decline decreases, indicating that the forward shock component has begun to dominate the light curve.

- A very fast radio flare associated with a gamma-ray superflare from the rapidly-rotating nearby dwarf star DG CVn (Fender et al. 2015; Figure 2 right). ALARRM was on target and observing DG CVn less than 6 mintues post burst resulting in the earliest detection of bright, prompt, radio emission from a high-energy transient ever made with a radio telescope. This is possibly the most luminous incoherent radio flare ever observed from a red dwarf star.

In addition to this ground-breaking robotic mode, a new programme to trigger on PTF transients has recently commenced. The type Ibc supernova SN 2014C, which is currently evolving into a highly unusual (overluminous, exceptionally slowly-evolving) transient, has been followed up through this programme. The AMI telescope is also being used for a large number of ad-hoc monitoring programmes of more slowly-evolving radio transients such as TDEs, X-ray binaries, novae, and flare stars.

Proposed work. I will carry out rapid radio follow up and monitoring of all transients discovered at radio, optical, X-ray, and γ-ray wavelengths. The well-sampled radio light curves will facilitate the

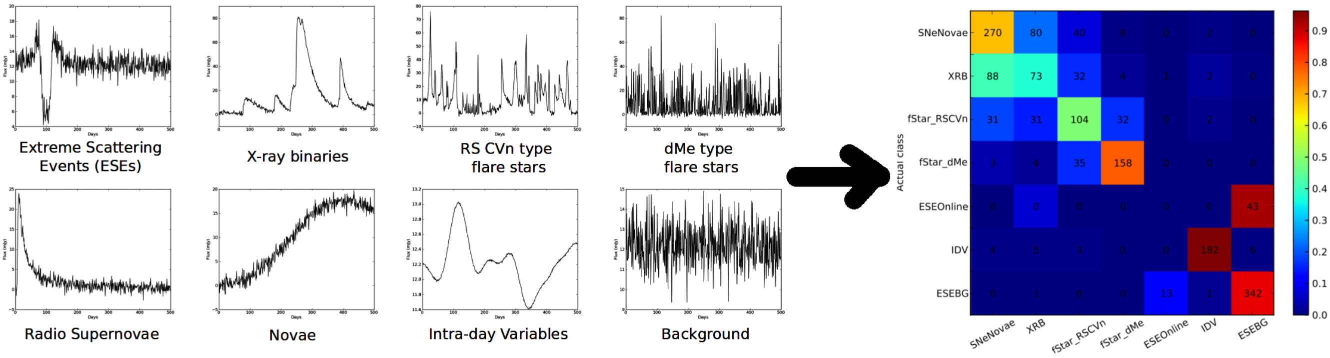

Figure 3: *Machine learning algorithm being developed to automatically classify radio transients using their radio and optical light curves. The resulting classifications are represented as a confusion matrix. Adapted from Rebbapragada et al. (2012).*

detailed study of the physics of the transients. The light curves generated from this project will also be used for the "Automated transient classification using artificial intelligence" project detailed in the next subsection. For this project, approximately two radio transients per month are expected to be detected. I will study and publish only a subset of the very high-impact transients among these, while the rest will be studied by a student/researcher in the supervisor's group.

1.1.2.3 Automated transient classification using artificial intelligence

Astronomy is entering the big data era. Once SKA and LSST become operational (early in the next decade), hundreds of transients will be discovered every week, and manual inspection of each transient will no longer be feasible. Rapidly vetting the transients and allocating follow up resources to the very high-impact ones will be crucial for maximising the knowledge from the transient surveys. One advantage that these next-generation surveys offer is fast cadence and joint observing, resulting in well-sampled radio and optical light curves. Machine learning will be necessary to automatically classify transients (or at least provide a preliminary classification) using their light curves. However, machine learning algorithm need to trained on existing data.

Proposed work. I will use the light curves from the MeerKAT, MeerLICHT, PTF, and AMI observations as training sets to develop an auto-classification algorithm for radio transients. As new data from these telescopes is obtained, the classifier algorithm will get better. Figure 3 shows a schematic.

1.1.3 Originality and innovative aspects of the research programme

The work proposed here facilitates significant advances in the field of radio transient astronomy. To make a strong impact on this field, the proposal introduces new techniques (rapid transient search, robotic follow up, and automated classification softwares, to name a few) to discover transients and maximise the knowledge obtained from them, and these techniques are easily transferable to other telescopes. In terms of science, this work addresses key unsolved questions in current astrophysics, such as the occurrence rate of radio transients, the inverse beaming fraction of γ-ray burst jets, and the time evolution of radio emission in various classes of astrophysical transients.

Radio transient astronomy is an exciting new field ripe for discovery, made possible by large recent technological advances, and requires novel, innovative methods. This proposal takes advantage of the cutting-edge capabilities of some of the most powerful and sensitive facilities on the planet such as the JVLA, MeerKAT-MeerLICHT, and ZTF. The proposed work employs new methods like near-real-time data processing and rapid multiwavelength follow up for maximally exploiting the new radio transient discoveries. Radio-optical surveys are also a novel concept; they are expected to be extremely productive in finding transients and understanding their nature. Joint surveys with MeerKAT-MeerLICHT and

JVLA-PTF/ZTF will serve as will serve as a benchmark for future radio-optical experiments, including SKA-LSST. Radio follow up and monitoring with the AMI telescope, which is the first robotic radio telescope of its kind and represents state-of-the-art, is yet another unique aspect of this proposal. Finally, as radio astronomy moves steadily into the big data regime, artificial intelligence techniques for dealing with data become more relevant, and the proposed work introduces radio transient astronomy to these techniques.

The proposed high-quality innovative research will give me the essential skills for working on future radio and optical transient facilities: SKA and LSST. It will thus open up the best career possibilities for me, and my existing collaborations with JVLA and PTF will invite new collaboration opportunities for the host institution.

1.2 Clarity and quality of transfer of knowledge/training for the development of the researcher in light of the research objectives

The host institution, Oxford, has recently secured participation in cutting-edge radio-optical surveys such as MeerKAT-MeerLICHT, and SKA-LSST. Although the research groups at Oxford specialise in data interpretation, modelling and simulations, the expertise in designing surveys, radio and optical data processing, and efficiently dealing with the large amounts of data is lacking. At the same time, I need to learn how to derive the best science from astrophysical data through interpretation and modelling. Thus, given the research objectives, high-quality transfer of knowledge will take place between the host institution and myself. The experience that I can offer the host institution is described below.

- **Expertise in radio and optical transient surveys.** As part of my Ph.D., I worked extensively on radio and optical transient surveys with JVLA and PTF. I also developed a basic software infrastructure for near-real-time radio transient search, transient vetting, and rapid multiwavelength follow-up. The discovery of several fascinating transients has demonstrated the success of the techniques that I developed. Using this expertise, I expect to make a valuable contribution to the host institution to execute joint radio-optical transient surveys and multiwavelength follow up observations. This is a very valuable resource for Oxford, and it comes at an opportune time, given that some of the radio-optical facilities will become operational by 2017.
- **Big data know-how.** Due to the sheer volume of the data generated by new telescopes, several challenges arise, including efficient data processing, data visualisation and analysis, and optimal use of computing resources. The know-how of big data is lacking in the astronomy research groups at the host institution. Since I have dealt with large volumes of data from the JVLA and PTF during my Ph.D., I can offer this extremely important knowledge to the host organisation.
- **Existing collaborations.** I am an experienced user of the JVLA and PTF, which are powerful radio and optical telescope facilities. My existing collaborations allow me to use these facilities frequently for transient search and follow up. Given the increased need for follow up resources in any transient search programme, the host institution will greatly benefit from my existing collaborations.

Moreover, working in the astronomy group at Oxford during the fellowship will give me opportunities to broaden my own knowledge in key areas of astronomy, work on new projects, and join new collaborations. These opportunities, described in detail below, will enhance my career prospects.

- **Access to new telescopes, surveys, and collaborations.** Oxford will be participating in major international surveys, listed above, with an aim of pushing new frontiers in time-domain astronomy, and addressing major problems in modern physics and astrophysics. The proposed projects will enhance my skills of dealing with data from the new generation of telescopes and prepare me for exploiting data from the SKA and LSST. The access to these new telescope facilities and participation in international collaborations will greatly enhance my career prospects.

- **Accretion and feedback in compact objects.** The host institution, Oxford, is home to a world-leading group in the area of accretion and outflows in compact objects. In particular, the proposed supervisor, Robert Fender, has made a significant contribution to the understanding of the connection between accretion and jets. While the subject is mostly new to me, I have done some work on accretion in AGN. Learning from leading experts in the area of jets should place me in a good position to work on transients powered by accretion and jet phenomena.

- **Teaching, mentoring, and public engagement.** I do not have substantial experience with teaching and public engagement. Under the guidance of astronomy faculty members at Oxford, I aim at honing these skills.

1.3 Quality of the supervision and the hosting arrangements

1.3.1 Qualifications and experience of the supervisor(s)

The supervisor, Robert Fender, is a world-leader in the field of radio transients, the research topic of this proposal. He is currently Professor of Astrophysics at the University of Oxford and also holds a Visiting SKA Professor position at The University of Cape Town. Previously he was Professor of Physics at The University of Southampton, and prior to that Universitair Hoofddocent at the Universiteit van Amsterdam. Prof. Fender has published more than 300 refereed papers since 1998 including prestigious journals such as Nature and Science. His publications have received more than 9000 citations; his first-author papers alone have generated more than 3000 citations. Prof. Fender has been awarded several prestigious prizes in research and teaching, and has an excellent track record in training young researchers. He has supervised six Marie Curie Fellows in the past. Of special relevance to this proposal, Prof. Fender is the PI of the AMI/ALARRM project, the co-PI of the radio transients survey with MeerKAT, a co-I on the ASKAP transients programs, a science team member on MeerLICHT.

1.3.2 Hosting Arrangements

The host institution, Oxford, is a world-class university both in teaching and research, and has the largest volume of world-leading research in the UK. The Department of Physics at Oxford is a highly collaborative department with world class facilities, public engagement activities, and a rich set of science seminar series. The department has provided research facilities in over 30 Marie Curie Actions under FP7 and H2020. I recently joined the astrophysics sub-department at Oxford, and I find myself already very well integrated within it. The research environment is excellent and it fosters innovation and collaboration. The sub-department has 12 faculty members, several of whom work in areas relevant to this proposal. Philipp Podsiadlowski works on theoretical aspects of the progenitors and remnants of cosmic explosions. Lance Miller works on black hole accretion and is the Oxford lead on the LSST collaboration. Steven Balbus is an expert on astrophysical fluid dynamics and magnetic fields, and has worked extensively on accretion disks and disk instabilities. Two visiting professors, Jocelyn Bell Burnell and John Miller, are experts on pulsars and compact objects.

The primary areas of Prof. Fenders (supervisor's) research team are radio transients, transient surveys and follow up, X-ray binary outbursts, accretion disks and astrophysical jets, and cataclysmic variables. His research team has expertise in radio transient phenomena and sophisticated computer programming, which is ideal for my training and transfer of knowledge to me. The team has access to high-class computing equipment and a wide range of telescope facilities, some of which form an important part of this proposal. Oxford is now a full member of the the SKA and LSST collaborations, which form the ideal career prospects for me after completing the Marie Curie fellowship.

1.4 Capacity of the researcher to reach and re-enforce a position of professional maturity in research

The proposed research requires the development of new tools (algorithms, strategies, and computer programs) for maximising the knowledge obtained from radio and optical telescopes. The projects are based on problem-solving via novel methods that need independent thought, optimisation, computer programming, participation in new collaborations, innovating new techniques and managing large projects. This skill set obtained through the proposed research will be crucial for my professional development. Through the detailed study of transients via radio-optical surveys and multiwavelength follow up, I will develop an understanding of the physics of the most energetic and rare processes in the Universe: astrophysical transients. During the fellowship, there will be opportunity to tutor students, and this will allow me to pass on my knowledge, and improve my skills as a teacher/mentor. With the proposed research, personal experience, and occasional guidance/advice from the supervisor, I thus will advance in my career to become an independent/mature researcher.

2 Impact

2.1 Enhancing research- and innovation-related skills and working conditions to realise the potential of individuals and to provide new career perspectives

The proposed research will substantially advance our knowledge of astrophysical transient phenomena. The research involves the planning and execution of radio-optical transient surveys, discovery and detailed study of transients, multiwavelength follow up, developing novel ways of rapidly processing and analysing large volumes of data, and innovating a fully-automated transient search and classification system. The proposed research and my personal experience as a Marie Curie fellow will therefore take my transient survey and data handling skills to the next level. From the research groups at the host institution, I will also greatly increase the knowledge on the physical processes driving radio transients. Overall, I will professionally develop as an expert in radio transients. All the skills acquired through this fellowship will be valuable for the next generation of radio-optical telescope facilities — SKA and LSST — and will significantly increase my career prospects.

The projects dealing with MeerKAT-MeerLICHT will involve collaborations between astronomers at Oxford, Nijmegen, and Cape Town from the outset, merging our complementary theoretical, instrumental and observational expertise. In the long-term, our joint research during the fellowship will be the foundation for lasting collaborations between these institutes. The majority of the SKA-mid project will come to Africa; the core will be constructed at the site of the South African SKA pathfinder, MeerKAT. Cooperation with South African astronomers will become even more important in future, because the new generation of radio telescopes is of great relevance to the European astronomy community. The competences that I acquire during the fellowship will enable me to work closely on SKA, MeerLICHT, and related projects, which will foster European-African partnerships in radio astronomy.

2.2 Effectiveness of the proposed measures for communication and results dissemination

Communication is the third and important aspect of this proposal. Dissemination of the research results to the scientific community will be done via publications in scientific journals. Additionally, I will present my research at conferences and seminars to make the astronomical community aware of the work done as part of this fellowship. I will rely on press-releases and publications in prestigious journals like Nature and Science for announcing important discoveries to the scientific community and to the public.

Public outreach and engagement activities are crucial in any kind of research. The public engagement planned for this proposal is through various effective channels: science exhibitions, open days and internet-based platforms. The Royal Society organises a Summer Science Exhibition each year. I will submit proposals each year for participating in the exhibition, and if selected, this will be a unique opportunity for me to showcase my research. Additionally, there are several "Physics Department Open Days" each year at the Oxford (host), aimed at increasing science awareness of the public. I will present my research during these open days and thus inspire children and students to take up astronomy as a career path. Chris Lintott, a professor in the Department of Physics and a a world-leader in citizen science, is PI for the Zooniverse project. This is an innovative and highly-successful web-based platform for public engagement, and I plan to integrate one my research projects with Zooniverse. Further, I will write blogs regularly to disseminate research highlights to the public via internet.

Exploitation of results and intellectual property rights will be facilitated by making the data and techniques generated through this fellowship readily available to the astronomical community. As mentioned earlier, the transient search and classification techniques innovated as part of the fellowship will be important for the planning and working strategy of other telescopes. Once the techniques have been developed and thoroughly tested, I plan to make the relevant software available to everyone via internet repositories such as GitHub. Finally, the data generated by this work will serve as a rich resource for the astronomical community. After the publication of results in scientific journals, the data will be released via internet in accordance with telescope policies.

3 Implementation

3.1 Overall coherence and effectiveness of the work plan

Three distinct, but related, projects have been proposed here to substantially advance the field of radio transient astronomy. The objectives of each project is clearly laid out. Each of them has a definite timeline (see Figure 4) and deliverables so that the entire action is successfully completed in 24 months. The management plan and strategies for regular assessment of progress (described in section 3.2) are robust for achieving the desired impact. The three projects will be the work packages and there will be two well-defined deliverables as outlined below. WP1.2 and WP2.1 are tentative, and subject to the data release policies of the telescopes and consensus among the members of the collaboration.

Work Packages titles: **(WP1)** Incoherent transient phenomena via joint radio-optical surveys and rapid multiwavelength follow up (months 1–16); **(WP2)** Robotic radio follow up with AMI (months 1–22); **(WP3)** Automated radio transient classification (months 17–22)
List of major deliverables: **(WP1.1)** Rapid data processing and transient search software (pipeline; month 18); **(WP3.1)** Automated radio transient classification software (month 24); **(WP1.2)** Data release for joint radio-optical surveys (month 24); **(WP2.1)** Data release for AMI light curves (month 24)
List of major milestones: **(M1)** WP1 is complete or nearly complete. Assess the outcome. WP3 begins. Plan the course of work for WP3. (month 16); **(M2)** WP2 and WP3 are complete. Assess the outcomes and estimate the progress made on deliverables (month 22).

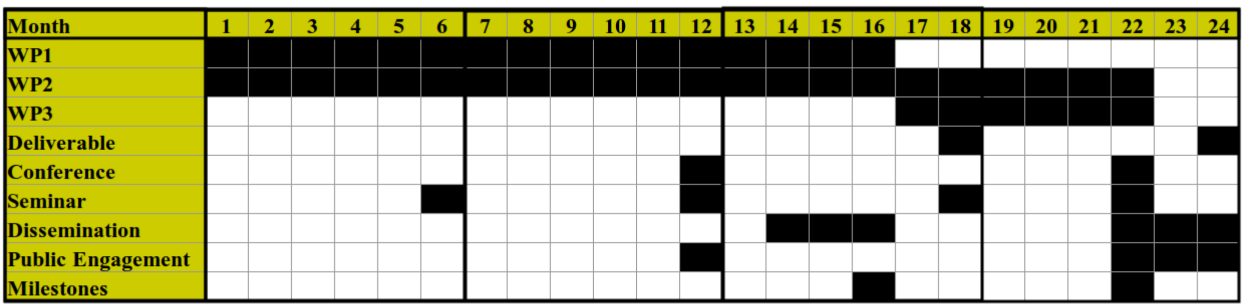

Figure 4: *Gantt Chart.*

3.2 Appropriateness of the management structure and procedures, including quality management and risk management

Project organisation and management structure. The work plan described above follows a logical work flow and makes regular assessment of progress (see below). The execution and management of projects will be done largely by myself. Prof. Fender will assist with the scientific management throughout the term of the fellowship. This management structure and procedure will ensure the best quality and timeliness of the proposed research. The supervisor's research group has regular weekly meetings to define milestones, evaluate progress, and discuss preliminary results. This means that any scientific or technical problems will be solved as quickly as possible, and the quality of work and progress can be monitored regularly. The financial management of the project will be done by the European Grants and Research Accounts Department at Oxford, which has highly experienced teams.

Risks that might endanger reaching project objectives. There are two areas which are high-risk. Firstly, the rates of cosmic explosions are not extremely well constrained and may be lower by the a factor of few than those listed in section 1.1.2. Even if this is the case, the detection of at least a few radio transients with MeerKAT-MeerLICHT and JVLA-PTF is expected. Secondly, MeerKAT-MeerLICHT are facilities under construction scheduled for completion in late 2016, but their completion deadlines may be pushed back by a few months. However, MeerKAT has strictly followed all the deadlines for deliverables that it has set in the past, and also the impact of construction delays, if any, will be mitigated by the use of existing telescope facilities, JVLA and PTF/ZTF.

3.3 Appropriateness of the institutional environment (infrastructure)

Adequate resources for the good implementation of the action will be given by the host institution, Oxford. The host will provide an office space and computing facilities within the Department of Physics. The supervisor's research group has a dedicated network of 16-core 64-bit computers with a total of 100 TB of disk space, sufficient for storing of large amounts data and rapid data processing. Oxford also offers state-of-the-art high-performance computers (Advanced Research Computing).

3.4 Competences, experience and complementarity of the participating organisations and institutional commitment

The beneficiary of this proposal, the University of Oxford, is a world-class university both in teaching and research, and has the largest volume of world-leading research in the UK. Oxford will provide me with facilities and opportunities for teaching, mentoring, and public engagement. The Department of Physics at Oxford has a rich set of science seminar series, which will help me stay up-to-date with the latest research in astronomy and related fields. Oxford will provide access to key international projects, telescopes, and collaborations, viz. MeerKAT-MeerLICHT, SKA-LSST, and AMI, around which this proposal is based. The astrophysics sub-department has several faculty members and research scholars who are experts in the fields of radio and X-ray transients, compact objects, accretion, jets, and other aspects of astrophysical transients. The research team under the supervisor, Robert Fender, has expertise in radio transient astronomy and sophisticated computer programming, which is ideal for my training. The astronomy faculty members at Oxford will provide essential advice, and also serve as research collaborators in some cases, for the proposed research projects.

References: ■ Anderson et al. 2014, MNRAS, 440, 2059. ■ Bannister et al. 2011, MNRAS, 412, 634. ■ Bower et al. 2007, ApJ, 666, 346. ■ Fender et al. 2015, MNRAS, 446, 66. ■ Frail et al. 2012, ApJ, 747, 70. ■ Gal-Yam et al. 2006, ApJ, 639, 331. ■ Gehrels et al. 2009, ARA&A, 47, 567. ■ Kasliwal 2012, PASA, 29, 482. ■ Kulkarni et al. 1998, Nature, 395, 663. ■ Michelson et al. 2010, Reports on Progress in Physics, 73, 7. ■ Mooley et al. 2015, ApJ, accepted. ■ Rebbapragada et al. 2012, ASKAP Memo 5. ■ Thyagarajan et al. 2011, ApJ, 742, 49. ■ Weiler et al. 2002, ARA&A, 40, 387.

4 CV of the experienced researcher

Kunal Mooley

Address: Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH
Email: kunal.mooley@physics.ox.ac.uk
Web: http://www.tauceti.caltech.edu/kunal
Tel: +44-7957583904

ACADEMIC QUALIFICATIONS

2015–	**Hintze Research Fellow, Oxford University**
2009–2015	Ph.D. (Astronomy), California Institute of Technology. Dissertation: Exploring the Dynamic Radio Sky
2007–2009	M.Sc. (Physics), Indian Institute of Technology, Bombay
2004–2007	B.Sc. (Physics), Fergusson College, Pune, India

RESEARCH INTERESTS

Radio transients and surveys; accretion and jets; gravity waves; star-formation

CONFERENCE TALKS, SEMINARS & COLLOQUIA

2015	Exploring the Dynamic Radio Sky (Dissertation talk, AAS 225, Seattle)
2014	a) Exploring the Dynamic Radio Sky: The 270 sq. deg Stripe 82 Survey (AAS 223, DC) b) Search for Slow Transients with the VLA (University of Sydney) c) Search for Slow Transients with the VLA (Curtin University) d) Search for Fast and Slow Transients with the VLA (Swinburne University of Technology) e) Transient Search with the VLA and India's role in Time Domain Radio Astronomy (Indian Institute of Astrophysics, Bangalore, India) f) Transient Search with the VLA and India's role in Time Domain Radio Astronomy (National Center for Radio Astronomy, Pune, India)
2013	a) Exploring the Dynamic Radio Sky (AAS 221, CA) b) Exploring the Dynamic Radio Sky (Locating Astrophysical Transinents, Lorentz Center, Netherlands) c) Exploring the Dynamic Radio Sky with the VLA (Radboud University Seminar, Netherlands) d) Exploring the Dynamic Radio Sky with the VLA (University of Groningen Seminar, Netherlands) e) Exploring the Dynamic Radio Sky (University of Southampton Seminar, UK) f) Transients & On-The-Fly Mosaicking with the EVLA (NRAO Lunch Talk, Socorro, NM)
2012	a) Search for Radio Variables and Transients in the E-CDFS (Young Astronomers Radio Astronomers' Conference 2012, Puschino, Russia) b) The PTF + VLA Stripe 82 Survey (PTF Annual Meet, UCSB KITP, CA)

REFEREED PUBLICATIONS

1. Discovery of Radio Luminous Explosions In the Spiral Arms of Nearby Galaxies
Mooley, K., Hallinan, G., Myers, S., et al. 2015 (**Nature**, to be submitted shortly)
2. The Caltech NRAO Stripe 82 Survey (CNSS) Paper I: The Pilot Radio Transient Survey In 50 deg^2
Mooley, K., Hallinan, G., Bourke, S., et al. 2015 (**ApJ**, accepted)
3. Study of X-ray Emission from an Old Open Cluster, M67
Mooley, K. & Singh, K. 2015 (**MNRAS**, accepted)
4. A Sensitive Search for Radio Transients and Variables in the Extended Chandra Deep Field South
Mooley, K., Frail, D., Ofek, E., et al. 2013, **ApJ**, 768, 165
5. B- and A-type Stars in the Taurus-Auriga Star-forming Region
Mooley, K., Hillenbrand, L., Rebull, L., et al. 2013, **ApJ**, 771, 110
6. The VLA-COSMOS Survey – VI: 3 GHz Continuum Observations
Smolčić, V., Novak, M., Bondi, M., et al. 2015 (**ApJS** submitted)
7. The XXL Survey: IX. Optical overdensity and radio continuum analysis of a supercluster at z=0.43
Baran, N., Smolčić, V., Milaković, D., et al. 2015 (**A&A** accepted)
8. New insights from deep VLA data on the potentially recoiling black hole CID-42 in the COSMOS field
Novak, M., Smolčić, V., Civano, F., et al. 2015 **MNRAS**, 447, 1282
9. New insights from deep VLA data on the potentially recoiling black hole CID-42 in the COSMOS field
Novak, M., Smolčić, V., Civano, F., et al. 2015 **MNRAS**, 447, 1282
10. Physical properties and environment of z>4 submillimeter galaxies in the COSMOS field
Smolčić, V., Karim A., Miettinen, O., et al. 2015 (**A&A**, 576A.127S)
11. X-Ray Transients in the Advanced LIGO/Virgo Horizon
Kanner, J., Baker, J., Blackburn, L., et al. 2013, **ApJ**, 774, 73
12. A multi-wavelength investigation of the radio-loud supernova PTF11qcj and its circumstellar environment
Corsi, A., Ofek, E. O., Gal-Yam, A., et al. 2013, **ApJ**, 782, 42
13. The Birth of a Relativistic Outflow in the Unusual γ-ray Transient Swift J164449.3+573451
Zauderer, A., Berger, E., Soderberg, A., et al. 2011, **Nature**, 476, 425

SUMMER SCHOOLS & WORKSHOPS

2015 Zooniverse and Big Data Workshop (Oxford)
2014 Astrostatistics Summer School (Penn State Univ, PA)
2011 a) CARMA Summer School (Bishop, CA)
b) Single Dish Summer School (Green Bank, WV)
c) EVLA Advanced Data Reduction Workshop (Socorro, NM)
d) ALMA Workshop (Pasadena, CA)
2010 Synthesis Imaging Summer School (Socorro, NM)

FELLOWSHIPS

2015–2017 Oxford Hintze Fellowship
2012–2014 NRAO Grote Reber Fellowship

TEACHING / MENTORING / JUDGING

1. **Teaching Assistantship at Caltech**
   a) Introduction to Modern Astronomy (Ay20)
   b) Undergraduate Cosmology (Ay21)
   c) Graduate Cosmology (Ay127)
   d) Undergraduate Electricity, Magnetism and Optics Laboratory (Ph6)
   e) Undergraduate Nuclear Physics Laboratory (Ph7)
2. **Mentoring Students at the Washington Elementary School, Pasadena**
   a) Brainstorming for Annual Science Fair Projects
   b) Teaching New Science Concepts
3. **Judging at Science Fairs**
   a) California Science Fair
   b) McKinley School Science Fair

OUTREACH AND EDUCATION

2012 Venus Transit Outreach Event, Caltech
2011 SN2011fe Supernova Outreach Event, Caltech
2001 IUCAA Open Day: Stargazing Night, Pune, India

RESEARCH FUNDING

2015 SWIFT Grant (Cycle 11), $15k

5 Capacity of the Participating Organisations

Beneficiary UOXF	
General Description	Oxford is a world-class university both in teaching and research, and has the largest volume of world-leading research in the UK. It is a member of the prestigious IARU and LERU university alliances. The University scholars have been the recipients of 51 Nobel prizes, among which six are from the Department of Physics.
Role and Commitment of key persons (supervisor)	Robert Fender is a Professor in the Physics Department at the University of Oxford. He also hold a position as a Visiting SKA Professor at The University of Cape Town. He is an expert in the areas of accretion and feedback, and radio transient astronomy. Previously he was Professor of Physics at The University of Southampton, and prior to that Universitair Hoofddocent at the Universiteit van Amsterdam.
Key Research Facilities, Infrastructure and Equipment	The Department of Physics is a highly collaborative department with world class facilities, public engagement activities, and a rich set of science seminar series. The department has provided research facilities in over 30 Marie Curie Actions under FP7 and H2020. Professor Fender's research team has access to high-class computing equipment and telescope facilities. His research team has expertise in radio transient astronomy and sophisticated computer programming, which is ideal for training and transfer of knowledge to recruited Experienced Researcher.
Independent research premises?	Yes. There are no conflict of interests.
Previous Involvement in Research and Training Programmes	Oxford has been awarded over 200 individual Marie Curie Fellowships over the seven years of FP7 and has participated in 53 successful FP7 ITN projects. In the first MSCA IF call under H2020 (September 2014), the University was awarded over 50 Individual Fellowships.
Current involvement in Research and Training Programmes	Oxford is currently participating in twelve successful Horizon 2020 ITNs. The university is presently supporting more than 80 MSCA research fellows.
Relevant Publications and/or research/innovation products	• Fender, R., Stewart, A., Macquart, J-P., et al. 2015, arXiv:150700729, *Transient Astrophysics with the Square Kilometre Array* • Anderson, G, van der Horst, A., Staley, T. D., et al. 2015, MNRAS, 440, 2059, *Probing the bright radio flare and afterglow of GRB 130427A with the AMI* • Fender, R. P.; Anderson, G. E.; Osten, R., et al. 2015, MNRAS, 446, 66, *A prompt radio transient associated with a gamma-ray superflare from DG CVn* • Pietka, M., Fender, R., & Keane, E. F. 2015, MNRAS, 446, 3687, *The variability time-scales and brightness temperatures of radio flares from stars to supermassive black holes* • Fender, R. & Belloni, T. 2012, Science, 337, 540, *Stellar-Mass Black Holes and Ultraluminous X-ray Sources*

6 Ethical Issues

6.1 Describe how the proposal meets the EU and national legal and ethics requirements of the country/countries where the task raising ethical issues is to be carried out.

Not Applicable. This research does not involve any aspects listed in the Ethics issues table. There are no security and third country issues involved either,

6.2 Explain in detail how you intend to address the ethical issues flagged

Not Applicable.

ENDPAGE

MARIE SKŁODOWSKA-CURIE ACTIONS

Individual Fellowships (IF)
Call: H2020-MSCA-IF-2015

PART B

"Radio-Optical Transients"

This proposal is to be evaluated as:

[Standard EF]