NEW ROBOTIC TELESCOPE: SCIENCE CASE

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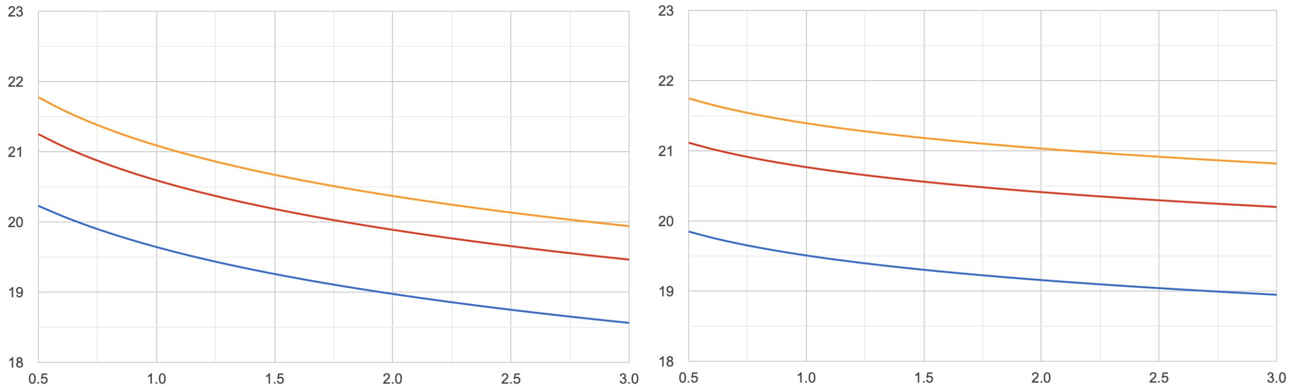
ABSTRACT

NRT is a project to build the world's largest (4m) robotic telescope (New Robotic Telescope - NRT) at the Observatorio del Roque de Los Muchachos, La Palma. The larger collecting area and lower mass of the 18 segment primary mirror (which will enable 30 second response time to event triggers) are the critical advances over current facilities, with both metrics being improved by a factor 4 over the current Liverpool Telescope (LT). By building NRT we aim to transform our users potential to lead scientific exploitation of the many massive new time-domain astronomical survey facilities being built by international partners. The scientific case for NRT has recently become even stronger with the discoveries of EM counterparts to gravitational wave (aLIGO/Virgo) and neutrino (IceCube) sources. A proposed spectroscopic classification survey (SPEC) will classify 10,000 objects per year and represents an increase of a factor of 5 over the current combined worldwide effort of all observatories (2,000/year). In addition to the transient classification survey, PI-led proposals to time allocation committees will also be supported.

Introduction

NRT represents a step-change in Northern hemisphere time domain capability and will revolutionise UK astronomy's exploitation of the transient sky. The principle gains over the current Liverpool Telescope come through an increased aperture (see Figure below) and reduced slew times (30 seconds to target).



Calculated Magnitude vs Seeing plots for r' imaging (left) and low resolution (R=350) spectroscopy (right) for 2.0-m (blue), 4.0-m (red) and 6.0-m (orange) apertures. Imaging is at SNR=40 (photometric accuracy 2.5% or polarimetric accuracy 4%) and spectroscopy at SNR=10 (sufficient for classification). Exposure times are short (30-s for imaging; 180-s for spectroscopy) to simulate rapid response to GRBs and high throughput (120 targets/night) spectroscopic classification. The large gain between 2.0m (LT) and 4.0m (NRT) is apparent, whereas going further (e.g. to 6.0m) would have less impact.

Wide-field optical surveys such as Pan-STARRS and the Palomar Transient Factory (PTF) heralded a new era for time domain science. Successor facilities such as the Zwicky Transient Facility (ZTF; Bellm+ 2019, PASP, 131, 018002) and ATLAS (Tonroy+ 2018, PASP, 130, 064505) now offer significant sensitivity and field-of-view improvements over their predecessors, and the Vera Rubin Observatory will soon probe unprecedented depths at high cadences. As well as direct discovery of transient sources, wide-field follow-up also complements other new methods of discovery. Follow-up of gravitational wave events for example will be one of the most important topics in time domain astronomy over the next decade, but the localisation of events from LIGO/VIRGO/KAGRA is poor and so large sky areas need to be surveyed in response to a trigger (Abbott+ 2016, PhyRevX, 6, 041015).

Survey facilities report large numbers of targets of opportunity, but observations on other telescopes in a response mode are crucial for the provision of the spectroscopic classifications and multiband light curves required for science exploitation. This exploitation is vital in order to maximise the potential of facilities to which STFC has made a strategic commitment, such as Rubin. Target of opportunity science, requiring priority overrides, is an uneasy fit for classically scheduled telescopes with visiting observers or large survey programmes. As the rate of targets increases, so does this incompatibility. The highly successful PESSTO programme demonstrates the value of dedicating large amounts of telescope time to transient follow-up (Smartt+ 2015, 579, A40), and NTT/SoXS (Schipani+ 2018, SPIE, 10702, 107020F) will be a powerful Southern hemisphere tool for the new transient era of fast discovery. However the range of ground and space-based discovery facilities means response capability is required for the entire sky, and in the North there is a clear capability gap which provides a unique opportunity for the UK to take leadership. A recent review of the transient classification outlook (Kulkarni, 2020, arXiv:2004.03511) demonstrated that the 2-metre robotic Liverpool Telescope is the third most productive transient classification facility in the world, after the 1.5m P60 telescope on Mount Palomar and ESO's 3.5m NTT. The LT is a world-leading facility, but the sensitivity and rapidity of the next generation of survey facilities will require a larger aperture and faster response. NRT will build on the LT's strengths and will be optimised for the transient follow-up task, using AI technologies to flexibly and automatically react to new discoveries in real time. At a latitude of 28 degrees North, the Canary islands is a Northern hemisphere location with access to a considerable fraction of the Southern sky; 60% of the main Rubin survey field will be observable by NRT with an airmass < 2.

The New Robotic Telescope will provide:

(i) ultra-rapid (<30s) spectroscopic and polarimetric follow-up of EM counterparts of GW (aLIGO/Virgo) and neutrino (IceCUBE/ANTARES) sources and new radio (e.g. LOFAR/SUPERB) and high energy (e.g. SVOM, Fermi, Einstein Probe, CTA) transients,

(ii) rapid (<1 hr) spectroscopy and polarimetry of (e.g. Rubin/ZTF) SNe to explore the shock-breakout phase and find spectral signatures of the progenitor, and of recurrent Novae which are the supposed progenitors of SNe-Ia,

(iii) timely (<24 hrs) and time resolved spectroscopy of the evolution of the previously mentioned sources, plus galactic transients such as outbursting binary X-ray transients and eruptive YSOs detected by VISTA/Pan-STARRS/Rubin, and

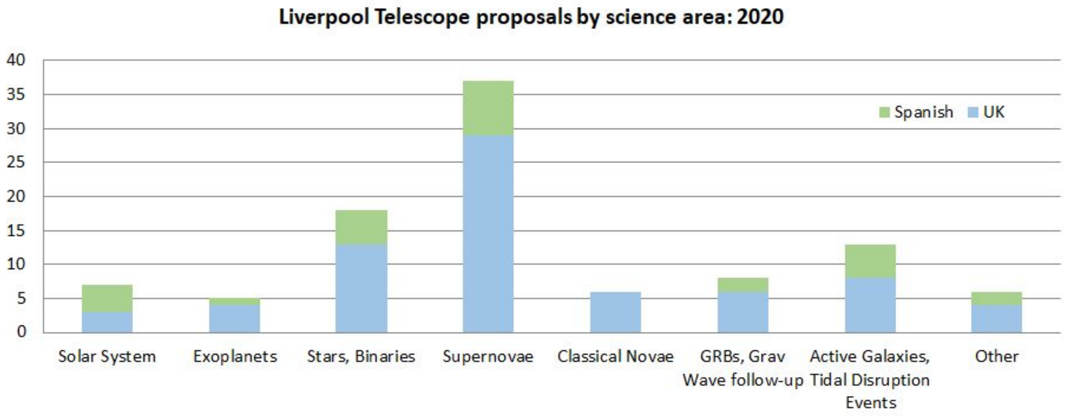
(iv) quasi-simultaneous (>24 hrs) spectroscopic and polarimetric monitoring of sources such as blazars (e.g. with Fermi, CTA) and changing look AGN.

Given the quantity and variety of transient discoveries we propose a time allocation model in which a significant fraction of the telescope time is devoted to a key science programme of spectroscopic follow-up (SPEC time). This time will be accessible to all the funding partners of the telescope. The remaining time will be split among the partners according to contribution and will be allocated via a typical time allocation process. We anticipate this time will be used for both further follow-up and exploitation of targets initially characterised via the SPEC programme, as well as for other science areas. Establishing this key science programme will maximise efficiency, ensure commensurate participation in the science outputs from all the partners, and is in line with recommendations from forward-looking reviews such as Kulkarni (2020).

The original NRT Science case (Copperwheat+ 2014, ExA, 39, 119) was published at the end of the project feasibility study, and was updated and revised in April 2019 as part of the NRT Phase A review. Here, we summarise the key time domain topics we anticipate will form the majority of the programme based on a combination of LT experience and a science forward look we have carried out.

Supernovae

The catastrophic nature of supernovae (SNe) make them powerful probes of the evolution and life cycle of different types of star. Type Ia SNe are also used as standarizable candles to measure cosmic distances and as a probe of dark energy. Supernova science is a core activity for the UK time domain community, and the LT receives more proposals based on the follow-up of supernovae and related stellar explosions than any other science topic.



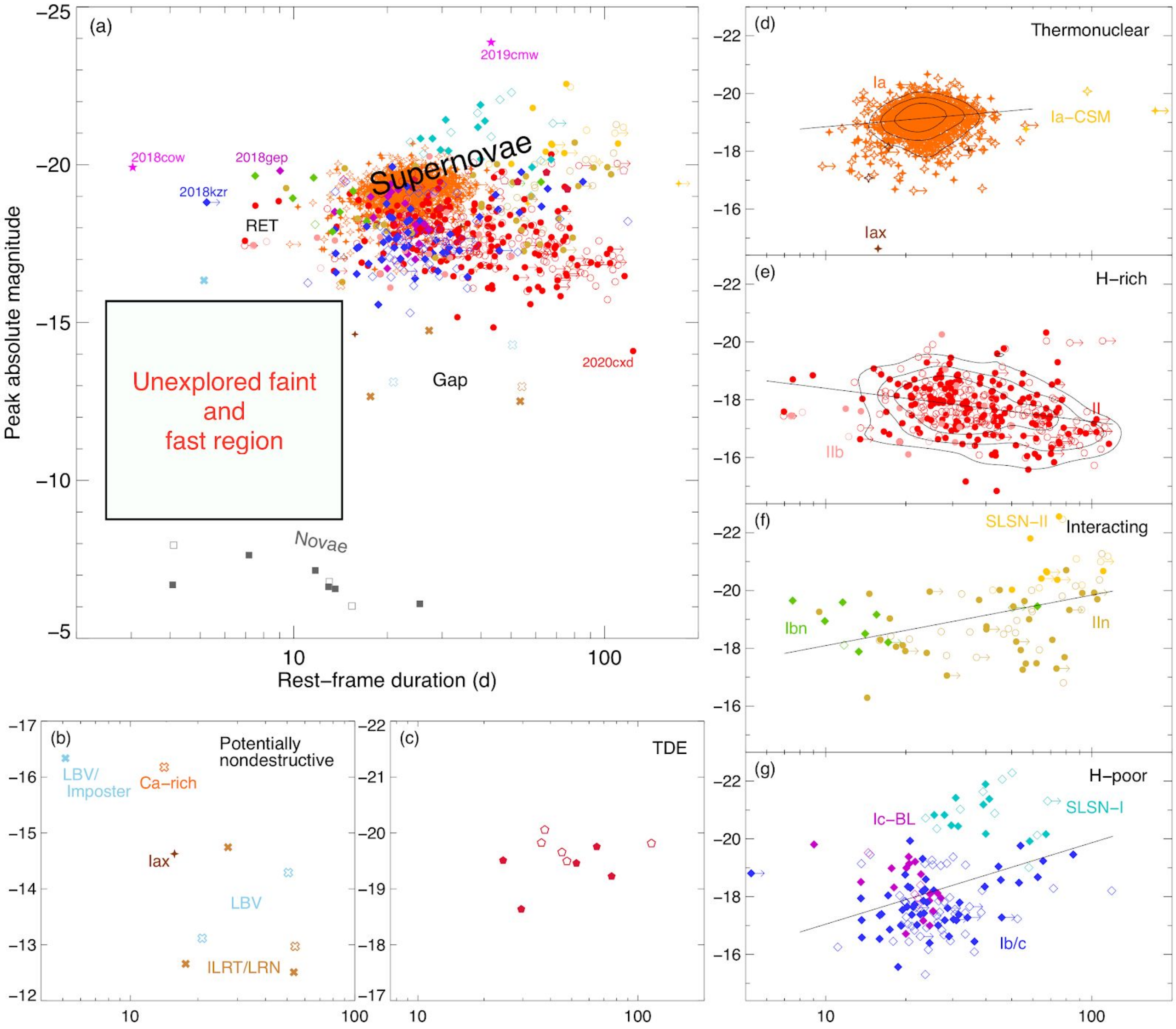
The modern survey era has seen the rate of discovery of new supernovae jump to thousands per year, providing scope for large scale and systematic approaches to classification and follow-up for population studies. Additionally it has seen the discovery of new and exotic phenomena which challenge existing explosion and progenitor models, such as superluminous supernovae. Nightly-cadence surveys such as ZTF and ATLAS are currently revealing a population of fast and blue transients: heralding the promise of the ‘faint and fast’ Rubin era. We note again that these searches cannot operate in isolation since they provide only limited photometric information, a limited cadence, and in some cases sacrifice spatial resolution for field of view. Multicolour light curves are crucial: without detailed photometry to provide supernova luminosities and colours, the physical parameters of the supernova explosions cannot be mapped, and the large samples for cosmological studies cannot be assembled. Photometric follow-up from telescopes such as NRT continues to be essential, even as the cadences of the surveys improve. Rubin for example will image the entire Southern sky every few days, but the observing cadence in the same filter will typically be much longer.

Type Ia SNe progenitors are binary systems consisting of a white dwarf and another star. Their apparent homogeneous nature provides a mature and direct probe of the dark energy that propels the accelerating Universe (Riess+ 1998, AJ, 116, 1009; Perlmutter+ 1999, ApJ, 517, 565). However, we are only just beginning to appreciate their observational diversity: there is evidence that there are multiple progenitor scenarios leading to a SN Ia explosion and the exact nature of the explosion mechanism (deflagration, deflagration-to-detonation, double-detonation…) remains unclear (Jha+ 2019, NatAs, 3, 706). Observing SNe Ia as early as possible after the explosion is a promising avenue for addressing these questions. For example, different explosion models produce differing ^{56}Ni density distributions, which is measurable via the early-time colour evolution (Noebauer+ 2017, MNRAS, 472, 278; Magee+ 2018, A&A, 614, 115). Early spectra enable measurement of the velocity evolution of the Si II line, a potential probe of the asymmetry of the ejectra. (Maund+ 2010, ApJ, 725, L167). Pre-peak spectroscopy allows for parameters such as progenitor metallicity and abundances of the outer ejecta to be associated with the light curve evolution. Long term photometric monitoring of samples probes the interaction of ejecta with the circumstellar environments (e.g. Silverman+ 2013, MNRAS, 430, 1030; Graham+ 2019, ApJ, 871, 62).

Core collapse SNe (CCSNe) are massive stars that end their lives with a rapid collapse and violent explosion (Smartt 2009, ARA&A, 47, 63). There are a wide range of subclasses based on observed differences in the light curves or spectra, which mostly reflect the size and degree of stripping of the progenitor at the time of explosion. Type IIb/c SNe do not show hydrogen lines (or strong silicon absorption which distinguishes them from Type Ia) as the progenitor loses most of its hydrogen envelope prior to the core collapse. A fraction of the envelope may be lost in some of the subclasses of Type II SNe too, with only those of Type IIP (the most common type) retaining most of their envelopes until explosion. There are likely many other parameters which affect the fate of the massive progenitor, such as the initial mass, metallicity, rotation rate, and the presence and properties of binary companions or magnetic fields. Early time optical spectra should show features generated by ionisation of the circumstellar media by UV radiation emitted during the shock breakout phase. (e.g. Gal-Yam+ 2014, Nature, 509, 471; Khazov+ 2016, ApJ, 818, 3). This ‘flash spectroscopy’ provides an insight into the early temperature evolution of the ejecta as well as the progenitor mass loss rate prior to the explosion. Since non-axisymmetric explosions are common in CCSNe there is a role for early-time polarimetry as well, to explore the geometry of the circumstellar ejecta and constraint the pre-explosion evolution.

Superluminous SNe (SLSNe) are a relatively new class (Quimby+ 2011, Nature, 474, 487) of extremely luminous transients. The mechanism for the highly efficient energy conversion has been explained in a variety of ways, with models including collisions of the ejecta with a dense shell of circumstellar matter, energy injection by a fast-spinning neutron star, or large ^{56}Ni masses produced by a pair-instability explosion (Nicholl+ 2013, Nature, 502, 346; Metzger+ 2015, 454, 3311). Events are rare and diverse, and so important questions are yet to be answered, such as the true cosmic rate of SLSNe and whether there is a continuum of transients connecting them with CCSNe. The small existing sample of well-observed events means early identification and exploitation of new candidates is vital to obtain the necessary multiband light curves from pre- to post-peak. Deeper surveys such as Rubin will find examples at higher redshifts, opening up the possibility of using this class for cosmological applications.

The ATLAS detection (Prentice+ 2018, ApJ, 865, 1) and resultant comprehensive exploitation of AT2018cow (Perley+ 2019, MNRAS, 484, 1031) revealed it to be one of the first of an exotic new class of ‘fast and blue’ transient. The first spectrum of this object was obtained with the LT, and that rapid response coupled with the subsequent nightly monitoring of the spectral evolution is an exemplar of the work which NRT will do in the high cadence discovery era. The rapidly growing class of fast and luminous blue transients defy current supernova models: possible interpretations include a relativistic jet within a fallback SN, or the tidal disruption of a star by an intermediate mass black hole. In the next decade the rate of transient detection will be of orders of magnitude greater, providing large samples of the most rare and unusual subtypes.



Duration-luminosity plot for 1194 classified ZTF Bright Transient Survey transients at m<18.5 satisfying a strict quality cut (filled points) and 961 additional transients with usable timescale measurements (unfilled points) (adapted from Perley et al. 2020). Rubin is expected to find many transients in the previously unexplored "faint and fast" region that will require a spectral classification by NRT.

Finally in this section, we note that the modern survey era provides the scope for large-scale searches for strongly lensed supernovae. Strong gravitational lensing of variable objects (such as a quasar or a supernova explosion) can be used as a tool to probe cosmological parameters such as the energy content of the Universe and its expansion history. Multiple images of transient events are not observed simultaneously due to their different paths through the Universe and lens; these time-delays between images are a direct probe of the Hubble constant (Refsdal, 1964, MNRAS, 128, 307). Lensed supernovae (LSNe) will be better cosmological probes than lensed quasars, as they have fast rise times, well-understood light curves and SN Ia have standardisable luminosities (Phillips, 1993, ApJ, 413, 105). While only two LSNe have been discovered to date (Kelly+ 2015, Science, 347, 1123; Goobar + 2017, Science, 356, 291), Rubin is forecast to discover ~50 type Ia LSNe per year (Goldstein+ 2019, ApJS, 243, 6). The observing cadence of Rubin alone does not yield sufficiently many LSNe with accurate and precise time delays (Huber+ 2019, A&A, 631, 161). There is therefore a critical need for high cadence, multiband monitoring of future Rubin LSNe; as well as the confirmation spectroscopy necessary to determine that a candidate is indeed a lensed SN, rather than a newly varying AGN. With a typical peak i-band magnitude of 22.7 the NRT is ideally suited to this task (predicted exposure time of 2400-s for SNR=10).

Gamma-ray Bursts

Gamma-ray bursts (GRBs) are the most energetic explosions to be detected in the Universe and offer unique access to regions of extreme physics: ultra relativistic speeds, strong gravity and intense magnetic fields, as well as acting as luminous stellar beacons that probe conditions in the early Universe. Long GRBs are thought to be associated with the death of massive stars (Woosley+ 1993, ApJ, 405, 273; MacFadyen+ 1999, ApJ, 524, 262), as confirmed by observations of nearby events (e.g. Galama+ 1998, Nature, 395, 670; Stanek+ 2003, ApJ, 591, 17; Hjorth+ 2003, Nature, 423, 847) and their interpretation (e.g. Iwamoto+ 1998, Nature, 395, 672; Mazzali+ 2003, ApJ, 599, 95; Mazzali+ 2005, Science, 308, 1284). The GW170817 gravitational wave event confirmed the association of short GRBs with neutron star mergers (Evans+ 2017, Science, 358, 1565), and has further accelerated interest in these sources.

GRB afterglows fade on timescales of minutes, and so the real-time response necessary for optimal exploitation of GRB detections make robotic telescopes powerful tools for this science case. LT has long responded automatically to triggers from the Neil Gehrels Swift Observatory and operates an automated observation pipeline which is designed to detect afterglows and execute a customised observing strategy based on brightness (Guidorzi+ 2006, PASP, 118, 288). A capability gap was identified for early-time polarimetry of afterflows, leading to the in-house development of the novel line of RINGO fast polarimeters. The subsequent measurements of early-time GRB polarisation (Mundell+ 2007, Science, 315, 1822; Steele+ 2009, Nature, 462, 767; Mundell+ 2013, Nature, 504, 119) are a clear case of UK scientific leadership and the only method for measuring the geometry of the magnetic fields that collimate the jets in these objects. The fourth generation of high speed polarimeter on the LT, MOPTOP, was awarded STFC PRD and Consolidated Grant funding and has recently been commissioned on the LT.

Swift and Fermi continue to be productive sources of GRB triggers, and from 2021 they will be joined by the SVOM mission. Given the strong synergy between this topic and the rapid response capability of robotic telescopes, we anticipate GRB follow-up continuing to be an important part of the NRT science portfolio. This science case is an important driver for the telescope design: the fast-fading nature of GRB afterglows means target acquisition time is at least as important as aperture for follow-up. Rapid IR imaging or spectroscopy is necessary to estimate the redshift of any event, and so there is a crucial need for ground based follow-up to, for example, identify the rare high-redshift events that can be used as cosmic beacons. With fast polarimetry a particularly unique selling point, MOPTOP has been designed with the intention that it will be transferred to NRT during commissioning (“NR-MOPTOP”), enabling from soon after first light the capability to polarimetrically characterise the majority of GRB afterglows. NRT will dedicate the focal station on the straight-through port for polarimetry, which will result in a further improvement in polarimetric accuracy compared to the folded LT beam. Combined with world-leading 30s response time of NRT these improvements will allow the prompt emission from GRBs to be constrained in ways that are impossible on any other current or planned telescope. The increased polarimetric accuracy and improved sensitivity of NR-MOPTOP will also broaden its range of potential science applications in other fields.

While Swift is sensitive to gamma-rays up to 150 keV: the Cherenkov Telescope Array (CTA) will begin science operations in 2021 and will open up the time variable sky at very high energies (~TeV). The Northern component of CTA will be located on La Palma and so NRT will be ideally placed to exploit CTA targets of opportunity. In recent years CTA precursors such as MAGIC have detected gamma-rays from three different GRBs, implying radiation at these energies may be a fairly common output from GRBs. For example GRB190114c (MAGIC Collaboration, 2019, Nature, 575, 455) was the first GRB detected at TeV energies and was associated with a bright prompt and afterglow emission spanning the electromagnetic spectrum down to radio wavelengths. Optical imaging and polarimetry with LT/RINGO3 and the MASTER telescope showed a low degree of polarisation (<7.7%) of the afterglow (Jordana-Mitjans+ 2020, ApJ, 892, 2). This coupled with the bright prompt and afterglow emission can be explained by dissipation of magnetic energy from (and consequent destruction of) the order in the outflow magnetic fields. The much improved sensitivity and field-of-view of CTA should see it provide a wealth of high energy data on GRBs and other transient sources, which coupled with fast optical polarimetry will provide a deeper insight into the properties of the jet magnetic fields, leading to a greater understanding of initial ejection and collimation processes.

Finally, we note that survey capacity has advanced to the point where a high energy trigger is not essential for GRB detection. The gamma-ray emission from GRBs is highly collimated, so only a small fraction of the cosmic population are detectable. It follows that there are a larger number of off-axis 'orphan' afterglows with no detectable high energy component. For example Law+ (2018, APJ, 866, 22) reported the discovery of a slowly-evolving radio transient which they claim is consistent with the afterglow of a far-off-axis orphan long GRB. Optical surveys, as well as new X-ray facilities (SRG/eROSITA) will find many events with orientations closer to the jet axis, making them strong candidates for rapid optical follow-up. ZTF has discovered a number of examples (e.g. Ho+ 2020, arXiv:2006:10761) thanks to the development of a real-time pipeline for detection of candidate afterglows or kilonovae in the transient stream (Andreoni+ 2020, arXiv:2008.00008). The expected rate of discovery of such events at optical wavelengths with Rubin is high (0.3-1 per night) (Ghirlanda, 2015, A&A, 578, A71). This much larger and more complete sample will provide constraints on the jet angular structure, Lorentz factor distribution, and the rate of GRBs in the Universe.

Electromagnetic counterparts of gravitational wave sources

The discovery potential of non-EM messengers for transient detection is immense, and the campaigns around the detection of gravitational wave emission from the GW170817 neutron star (NS) merger (Abbott+ 2017, PhRvL, 119, 161101) and the neutrino detection from the blazar TXS 0506+056 (IceCube Collaboration+ 2018, Science, 361, 147) highlight the importance of EM follow-up campaigns for verification and elucidation of the event. The positional uncertainties of such detections are and will remain large. The difficulty of counterpart detection is not just the transient discovery itself, but distinguishing the true counterpart from the large numbers of unrelated candidates in a sky region of many square degrees. In particular the GW170817 campaign demonstrated the importance of identifying the counterpart rapidly, since the first 12 hours showed a very rapid spectral and photometric evolution (e.g. Pian+ 2017, Nature, 551, 67; Smartt+ 2017, Nature, 551, 75; Tanvir+ 2017, ApJ, 848, 27). The early observations were key to the physical understanding of the event, and the unique rapid colour evolution of the 'kilonova' (in which the isotropic EM emission is due to the radioactive decay of heavy r-process nuclei) in the early hours suggests that very early colours will be the mechanism through which future counterparts are confirmed. Detection of new events and characterisation of the early evolution of these sources is of the highest priority to the time domain community: open questions include whether all NS-NS mergers produce short GRBs, whether outflows from NS-NS and NS-BH mergers are similar, and the properties and structure of the jet (Lamb+ 2017, MNRAS, 472, 495; Kasliwal+ 2017, Science, 358, 1559). Gravitational wave events also offer an independent means of measuring the Hubble constant (Schutz 1986, Nature, 323, 310; Abbott+ 2017, Nature, 551, 85), but an EM counterpart must be identified to do this with precision due to a model degeneracy between inclination and distance.

The third LIGO/Virgo science run recently concluded, and, while over a dozen potentially EM bright events were pursued by the community, no new counterparts were positively identified. This is a new and emerging field, but based on the evidence to date it seems likely that the GW170817 counterpart was exceptional and future detections will be significantly fainter. While the 2m LT continued to be one of the most active follow-up facilities during the third science run (Kasliwal+ 2020, arXiv:2006.11306) the majority of the data taken was photometry, compared to the earlier runs where most observations were spectroscopic classifications. This highlights two points: the important role for rapidly reacting robotic telescopes in these science programmes, but also the need for a larger aperture in science runs to come. NRT will complement new discovery facilities such as the UK-led GOTO project on La Palma. The 4-metre NRT will be able to undertake follow-up spectroscopy of any transient discovered by GOTO, and automated cooperation between these two robotic facilities provides the potential for colours and spectroscopic classifications within minutes of candidate discovery.

AGN and TDEs

Multiwavelength variability studies are a key technique for exploring the structure of the material surrounding the central engine in AGN. 'Disk reverberation mapping', the study of the time delays between light curve measurements of physically-connected emission regions associated with the central supermassive black hole, is a proven observational test of accretion disc structure (Blandford and McKee 1982, ApJ, 255, 419; Peterson and Horne 2004, AN, 325, 248). Such studies, often quasi-simultaneous with X-ray or UV observations, probe the unresolved accretion structure and the broad line region, allowing the investigation of links between black hole mass, mass accretion rate and disk geometry (see, e.g. Starkey+ 2017, ApJ, 835, 65). Polarimetric monitoring of blazars has also been a productive area for the LT; for example the campaign surrounding the 2015 outburst of OJ287 enabled the measurement of the rotation rate of the black hole, and the confirmation of the loss of orbital energy to gravitational waves within two per cent of the prediction from General Relativity; the first indirect evidence for the existence of a massive spinning black hole binary emitting gravitational waves (Valtonen+ 2016, ApJ, 819, L37). This is an important result in the context of future Pulsar Timing Array efforts to directly detect gravitational waves from such systems. A typical observing strategy for AGN monitoring campaigns might involve a daily observing cadence over many months, with each visit to the target only minutes in length. The flexibility and low overheads (rapid target acquisition) from a robotic telescope clearly make it a better option for such campaigns compared to a visitor or service mode observatory. NRT will greatly improve the scope of studies such as these: long term monitoring campaigns are excellent 'observing queue fillers' for a telescope focused on target of opportunity science, and the NRT design goal of a world leading acquisition time will greatly improve the efficiency of short visit, long term monitoring programmes, enabling larger samples of objects.

Returning to targets of opportunity, tidal disruption events (TDEs) are events in which stars are torn apart by tidal forces near supermassive black holes. Candidate flares need to be classified in order to catch the rising emission and constrain the time of disruption, and then regular monitoring over the decay (lasting tens to hundreds of days) in order to constrain the models of mass accretion rate. Discovery channels for new events are UV/optical or X-ray surveys, but the two populations show differences: many of the UV/optically detected events do not produce X-rays. Explanations include the reprocessing (from soft X-ray to UV/optical) of photons in an optically thick shell of material (e.g. Guillochon+ 2014, ApJ, 783, 23) or that the UV/optical photons are produced by interactions in the debris stream (e.g. Piran+ 2015, ApJ, 806, 164). The number of known events has been small, but the capabilities of modern surveys are rapidly moving this field from single-object to population studies. van Velzen+ (2020, arXiv:2001.01409) for example reported 17 new events recovered from the first 1.5 years of ZTF operations, and the yield from Rubin is anticipated to be of the order of 1000s per year (Bricman & Gomboc, 2020, ApJ, 890, 73). The key to unlocking this population is identification and rapid spectroscopic characterisation of candidates. Spectral line ratios depend on the radii of emitting regions (Roth+ 2016, ApJ, 827, 3) and blueshifts constrain the presence of outflows and winds (Holoien+ 2019, APJ, 880, 120). While these transients are often bright, a high S/N is required since they are located in the brightest regions of their host galaxies, and so the 'background noise' is high.

Exoplanets and Solar System bodies

The discovery and characterisation of such systems is a key component of STFC's strategic agenda, and the flexibility of the robotic LT scheduler has shown that transit monitoring programmes can be combined with other time critical observations to maximise telescope efficiency and will be a key science area also for NRT. Time series photometry is a powerful tool which complements the high resolution spectroscopy used for radial velocity work. Insights from photometry include the determination of precise system parameters through light curve modelling, the inference and characterisation of third bodies through transit time variations, and the probing of atmospheric composition through multiband studies. However, while members of the UK community will have access to a number of high resolution spectrographic options in the coming decade (such as the repurposed Isaac Newton Telescope), there are relatively few UK options for time resolved photometry in the Northern hemisphere. TESS and PLATO will find a zoo of new exoplanets which will need ground-based characterisation. These surveys will target bright host stars to maximise the potential for follow-up. This, combined with the large aperture of NRT, provides the potential for a wider variety of time variable signatures to be explored for large numbers of exoplanets, such as transit spectroscopy and polarization, and detection of debris discs. Small stars, which may house Earth-sized worlds, will be selected for follow-up. Targeting late type stars has paid off immensely with the discovery of an Earth sized world around Proxima Centauri, and the characterisation of seven such planets in the TRAPPIST-1 system, a science programme in which the LT played and continues to play a prominent role (Gillon+ 2017, Nature, 542, 456). The TRAPPIST successor array SPECULOOS will probe over 1000 ultra-cool stars and brown dwarfs over the next decade for transits from Earth-sized planets, and NRT will be ideally placed to follow-up targets found with the northern array on Tenerife (Delrez+ 2018, SPIE, 10700, 21).

Within the Solar System the cadence and depth of new surveys have led to, for example, the first identifications of the first minor planets with interstellar origins (Meech+ 2017, Nature, 552, 378; MPEC 2019-R106). Photometry and spectroscopy of such systems can be used to constrain the physical and chemical processes involved in planetary formation in other extrasolar systems (Fitzsimmons+ 2019, ApJ, 885, 9). Small bodies inform our understanding of the composition of the protoplanetary disk and the evolutionary history of the Solar System. Near Earth asteroids are of additional interest due to their Earth impact potential, or as targets for sample collection or even economic exploitation in the medium to long term. Surveys such as ZTF and Rubin offer the possibility for a comprehensive census of such objects (see, e.g. Bolin+ 2020, arXiv:2008.05384), and the robotic operations model of NRT allows rapid follow-up of new discoveries to solve the orbit arc. It is a target requirement of NRT to provide non-sidereal tracking with autoguiding, which is necessary for spectroscopy of Solar System bodies, and is a capability which the LT does not offer. The range of NRT instrumentation will contribute to understanding the physics of individual Solar System objects, probing for example the YORP effect in asteroids, and making simultaneous spectroscopy and polarimetry of small bodies in conjunction with rendezvous missions (e.g. Psyche, Lucy) for gas and dust composition and dynamics.

Proposed Time allocation model / SPEC survey

The majority of LT time is allocated via biannual calls for proposals to three committees representing the UK, Liverpool JMU and Spanish user communities. While this generally works well it has some flaws: the nature of target-of-opportunity science means individual targets cannot be easily assigned to specific users, leading to some duplication of observations for high profile targets. For NRT, on which we anticipate early-time transient classification to be a major activity, there is also the worry that a particular science PI might `waste' a large fraction of their individual time allocation following up transients which after identification turn out not to match their particular science case, but may well be of use to a different PI. There is clear value to both PIs in coordination, as well as rapid propagation of results to the time domain community. Cenko+ (2020) makes the recommendation: *‘ToO policies are constructed to encourage groups to pool resources, work together (where sensible), and maximize the science possible from any given dataset’.*

The final time allocation model will be a matter for discussion by the telescope stakeholders, including STFC. However, the NRT project will advocate a hybrid model in which the available telescope time is split between a traditional committee-allocated model, and a Key Science Programme to be undertaken as a joint venture between all the partners. We refer to this programme as ‘SPEC’ time, as we imagine it will largely consist of spectroscopic, transient response observations. The purpose of SPEC is to respond to the challenges of time domain science in the upcoming era. The coming decade will see an unprecedented rate of transient triggers; a huge increase in the number of possible targets which will interest different scientific communities. Targets will be prioritised by transient brokers based on limited information. An open and collaborative approach to the follow-up strategy will maximise efficiency, widen the user base and enable equal access to the classification spectra. Data obtained via this programme will be made available to all partners in the NRT project. The relative financial and in-kind contributions of partners will be recognised by allocating pro rata representation on the collaborative science team which will plan and schedule the SPEC programme. The science working groups would report to this team in order to optimise the target selection strategy.

Our current proposal to the project board is that ~40% of the total telescope time is devoted to the SPEC programme, with the remaining time allocated via time allocation committee(s). This will permit classification of 10,000 targets per year brighter than $r=20.5$. This represents a factor of 5 increase over the number of spectral classifications (2012) delivered worldwide in 2019 (Kulkarni, S, 2020 arxiv.org/2004.03511) by the combined resources of the entire astronomical community. The STFC investment in NRT will buy access to all of this SPEC time for the UK community, as well as a pro rata share (~15%) of the remaining time based on the contribution to capital and operation costs. To illustrate how this would work for a particular science user, they might be an active participant in the collaborative SPEC programme, but also have applied for an individual and proprietary allocation in the UK time. Following discovery of a particularly interesting target via SPEC, they might trigger their own time in order to intensely monitor its spectral and photometric evolution. Or they might use their allocation to pursue one of the other science cases discussed in this document, such as the long term monitoring of a blazar or the study of exoplanet transits.

APPENDIX 1 - NRT DESIGN OVERVIEW

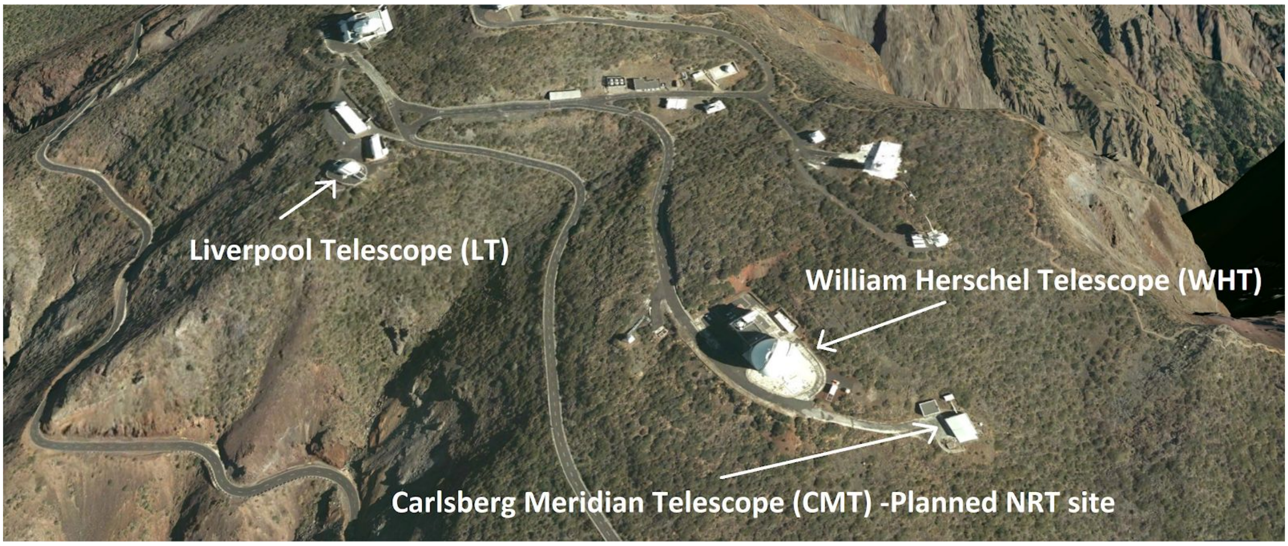
The design of the telescope is driven by 4 key requirements identified in our Phase A design study:

1. A 4m equivalent aperture to provide sufficient sensitivity to execute the key spectroscopic science programmes (see Science Case above).
2. A rapid slew speed and fast time-to-settle to allow science exposures to begin within 30-seconds of an observation being scheduled and with a blind pointing accuracy <5 arcsec rms. This enables the key science case of prompt phase GRB polarimetry as well as directly improving the efficiency of the planned spectroscopic classification survey.
3. Sufficient flexibility (in instrumentation and capabilities) to support not only the currently identified science cases but also those that will only emerge during the ~25 year operational lifetime of the facility, including the ability to switch between any instrument within 10 seconds.
4. Capable of autonomous operation, not only in terms of the scheduling and execution of observations, but also through fundamental system reliability delivered by systems of redundancy and automated fault recovery.

The overall design philosophy adopted is to wherever possible adopt and modify existing designs based on either the Liverpool and GTC telescopes (which the LJMU and IAC teams are intimately familiar with both from the design and operational phases) wherever they can be shown to meet the requirements.

The basic telescope configuration is Richey-Chretien with a 4m equivalent, 18 segment primary mirror and a final focal ratio of f/7.5. In a general departure from previous 4-m class telescope designs, we have selected a segmented design for the primary mirror. Such an approach has only been previously used on 8-m class telescopes and the 4-m Semei telescope currently being commissioned in Japan. ZEMAX and POPPY analysis showed that either a monolithic or an 18- hexagonal segment approach was capable of delivering an image quality that degrades the on-axis 80% EE by less than 0.2 arcsec over the median site value (1.3 arcsec) over the wavelength range of 0.35 to 2.0μm. Using a simple two-element fused-silica field-corrector will give a field of view of 15 arcmin diameter. As a future upgrade a 3-element Wynn corrector has also been designed which would deliver a 30 arcmin field of view.

The telescope will employ a conventional yoke/Serrurier-truss alt-az mount with a Cassegrain A&G box that hosts multiple instruments simultaneously to deliver a change time of <10 seconds and supporting a field of view of 30 arcmin at the straight through port and 15 arcmin at the eight side ports. The secondary mirror will be a monolithic element supported by a top end ring and allowing adjustment via a hexapod for focus and active collimation compensation. The telescope will be housed in a fully opening "clamshell" enclosure based on a scaled up version of the LT design and sited adjacent to the decommissioned Carlsberg Meridian Telescope (CMT) at ORM, La Palma. The clamshell design has particular advantages for a fast-response robotic telescope in providing access to all areas of the sky.



APPENDIX 2 - Baseline Instrumentation Plan

Based on an analysis of the science case we have developed a baseline, two-generation instrumentation plan for the telescope. Generation 1 aims to provide a basic set of low-cost, simple, high-throughput instruments that enable many of the key science cases to be delivered from soon after first light. It is based around the development of two new instruments (NR-SPRAT and NR-IMAGER) as well as the transfer of two existing instruments from LT to NRT (NR-MOPTOP and NR-RAPTOR). A summary of the properties of the first light instruments is shown below.

INSTRUMENT	**Wavelength**	**Field Of View**	**Notes**	**Science Cases**
NR-SPRAT	3750 - 7500 Å	12 x 12 arcsec	IFU Spectrograph R=360	Type Ia SNe, Type II SNe, unknown transients (e.g. AT2018cow), strongly lensed SNe, GW counterparts, TDEs, exoplanets, solar system bodies
NR-IMAGER	3500 - 10000 Å	7.5 x 7.5 arcmin	*ugriz* filter set	Superluminous SNe, strongly lensed SNe, exoplanet transits
NR-MOPTOP	4000 - 8000 Å	5 x 5 arcmin	Polarimeter BVRI filter set	GRBs, blazars, unknown transients, CTA follow-up, GW counterparts
NR-RAPTOR	1.6 - 1.8 μm	3.2 x 2.6 arcmin	H band filter	Type Ia SNe, GW counterparts, faint red transients, dust forming novae

Generation 2 aims to supplement and in some cases replace the first light instrumentation suite over the first 5 years of telescope operations to provide full imaging and low and medium resolution spectroscopic capability over the optical and near-IR wavelength ranges. As described above, this plan is provisional and will be shaped further by the science working groups over the next few years as well as user feedback once NRT becomes operational. With this in mind we propose a new optical imager (GLIC) to replace NR-Imager by adding reimaging optics to increase the field of view to 15x15 arcmin and adding a wider range of filter options. Similarly a new polarimeter FullStokes will replace MOPTOP to provide full simultaneous colour capabilities with fast readout such that the instrument would provide linear and circular polarimetric capabilities at millisecond cadence. A new Imager Slicer IFU spectrograph will complement NR-SPRAT by extending the wavelength range into the near-IR. Finally in order to cover the broad wavelength range requirement at medium resolution a SoXS-like (Son of XShooter) instrument will be developed. As the rapid blind pointing capability for spectral classification would be covered by NR-SPRAT and the Imager Slicer instruments, a cross-dispersed long-slit instrument is proposed for the follow-up science spectrograph where rapid acquisition becomes less important. In the footsteps of SoXS, this long slit spectrograph is proposed to have a spectral resolution R~3500-5500 over a wavelength range of 0.36-1.83μm captured in a single shot.