Institute of Physics
Astroparticle Physics Group

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The LIGO laboratory near Livingston, Louisiana. On 11th February 2016, the LIGO collaboration announced the first observation of gravitational waves from the merger of a pair of black holes. A second gravitational wave event was announced on 15th June.

Dates For Your Diary

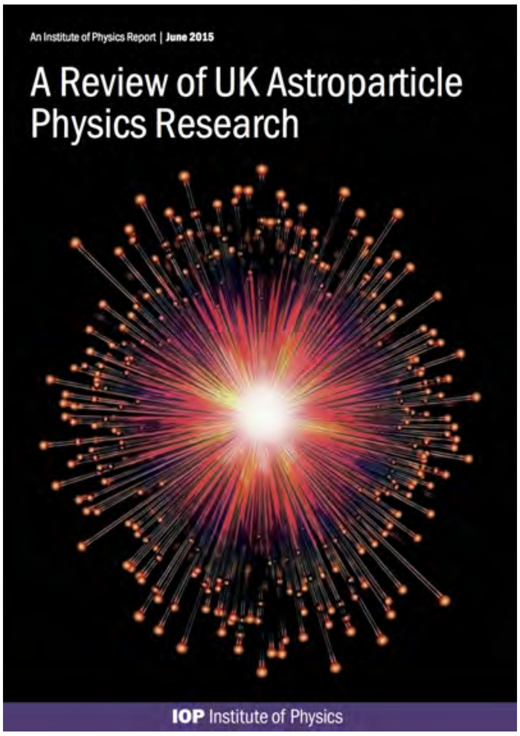
Joint IoP APP/HEPP Meeting - University of Sheffield	
13th January	Abstract submission deadline
13th March	Early registration deadline
3rd April	Registration deadline
10th–12th April	Conference
DMUK Meeting - University College London	
now – 18th January	Conference registration[1]
18th January	Meeting

[1]See goo.gl/BbGCde for registration and abstract submission.

Message from the Chair

It has been a little while since the last astroparticle physics newsletter and there have been several major advances in the field. The articles presented in this newsletter will give you an overview of some of the exciting research going on, all of which show the UK's strong international leadership on major astroparticle physics projects. Highlights include the detection of gravitational waves from aLIGO, the 2016 results from the Large Underground Xenon dark matter experiment, Neutrino experiments at the South Pole, interdisciplinary activities at Boulby Mine, and the latest news from the Cherenkov Telescope Array.

I would also like to point out the Review of UK Astroparticle Physics Research 2015, chaired by Alex Murphy, which further details the strength of the UK research activities in astroparticle physics, and also shows the strong impact and applied science that comes out of our research field. The full document can be downloaded from http://www.iop.org/publications/iop/2015/page_65866.html



Giles Hammond
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The Advanced LIGO (aLIGO) Project – Direct detection of Gravitational Waves

In the previous edition of the APP newsletter (January 2014), an article described how work on several Gravitational Wave detectors around the world was underway, increasing their sensitivity to a level where the detection of some event would become likely, rather than improbable as had been the case previously. In particular the article described the aLIGO project, where the two detectors in the USA (one in Livingston parish Louisiana, and the other on the Hanford nuclear site, Washington) were being upgraded. The spectacular fruition of this project was the announcement of the detection of gravitational waves. In fact, two definitive detections have been made, now known as GW150914 and GW151226 after the dates of detection, with their associated announcements made in February and June 2016.

The UK contribution to the aLIGO detectors was significant. There are two main forms in which this contribution was realised. Firstly, there is a global scientific collaboration associated with the LIGO detectors (the LSC or LIGO Science Collaboration), of which 9 UK universities have groups that are members. The LSC members provide the scientific input to all aspects of GW detection, such as instrument design, material science, source modelling, data collection and analysis and also an extensive public outreach program. Secondly, and more specifically, the STFC funded ALUK project provided the isolation suspensions for the test masses used in the aLIGO detectors. Although led from Glasgow University, this project also delivered contributions from Rutherford Appleton Laboratory and the Universities of Birmingham and Strathclyde, with theoretical support from Cardiff. As well as hardware, these groups also delivered the technical know-how to ensure that this contribution would realise the performance required in the detectors.

In fact, the result of this and the many other contributions from within LIGO and from the rest of the LSC, ensured that by the middle of 2015, the two detectors were nearing an operational state. The commissioning period was complete and the detectors were being characterised to understand all sources of noise in the output signal. To ensure data integrity, the detectors are "frozen" during operational runs, when essentially no changes are made, to ensure that the detector calibration is maintained and that noise sources are as stationary as possible, The first operational run (O1) was planned to start on September 18th, with a preceding engineering run where the detectors would be close to, or even at, operational sensitivity, starting at 0:0:0 UTC on September 12th.

The cataclysmic event producing the first gravitational-wave signal GW150914, took place in a distant galaxy more than one billion light years from the Earth. It was observed on September 14, 2015 by both of the LIGO interferometers; arguably the most sensitive scientific instruments ever constructed. LIGO estimated that the peak gravitational-wave power radiated during the final moments of the black hole merger was more than ten times greater than the combined light power from all the stars and galaxies in the observable Universe.

The signal was first identified by low-latency search methods designed to analyse the detector data very promptly, looking for evidence of a gravitational-wavelike pattern but without modelling the precise details of the waveform. These prompt searches reported the candidate event within only three minutes of the signals arriving at the detectors allowing any candidate event sky location to be passed on to electromagnetic (EM) observing partners for follow-up observations. In this case no counterpart EM signal was found.

After extensive comparison of the gravitational wave data with general relativistic models of compact binary systems our results indicate that GW150914 was produced by the merger of two black holes. These objects were determined to have masses of about 36 times and 29 times the mass of the Sun respectively, with the post-merger black hole having a mass of about 62 times the Sun's mass and showing clear evidence that it was a spinning (Kerr) black hole.

The estimated pre-merger masses of the two components in GW150914 make a very strong argument that they are both black holes, rather than other compact stars. The velocities of the component stars and separations are seen to be significant fractions of the speed of light and just a few times their Schwarzschild radii respectively. Black holes are the only known objects that can be this massive and compact enough to orbit each other as such small separations.

A few months after the first gravitational wave detection LIGO made another observation of gravitational waves from the collision and merger of a pair of black holes. This signal, called GW151226, arrived at the LIGO detectors on 26 December. In this case the black holes had masses of around 14 and 8 solar masses with the final spinning black hole having mass of around 21 solar masses. It originated from a location with similar distance to GW150914, around 1.4 billion light years away but from a different direction on the sky. Due to the lower mass of this system, the signal appeared in the LIGO detectors was longer in duration and therefore allowed better constraints to be placed on violations of general relativity. There are no hints that Einstein was wrong.

Both GW151226 and GW150914 indicate there could be many more stellar-mass binary black holes in the Universe than previously expected. These initial detections are an important first step towards understanding more about the population of these binaries, which until now has been completely hidden from us.

The first direct detection of gravitational waves and the first observation of a binary black hole merger are remarkable achievements, but they represent only the first page of an exciting new chapter in astronomy. The second observation run, O2, will start in December 2016 and will continue with short breaks through until May 2017 with the potential for the Italian-French interferometer Virgo to join the observation. The sensitivity of the detectors for O2 is expected to be a modest improvement on O1, but as the observed event rate scales with the sensitive volume, an increase in range of only 25% together with a longer observation will provide a significant increase in the event rate. Additional black hole binaries will surely be observed, and will increase our knowledge of their abundance, specific properties, and astrophysical formation history. This alone would be incredibly important science but equally exciting during the O2 run, would be the detection of coalescing binary neutron star systems. Our fingers are crossed.

Angus Bell & Chris Messenger
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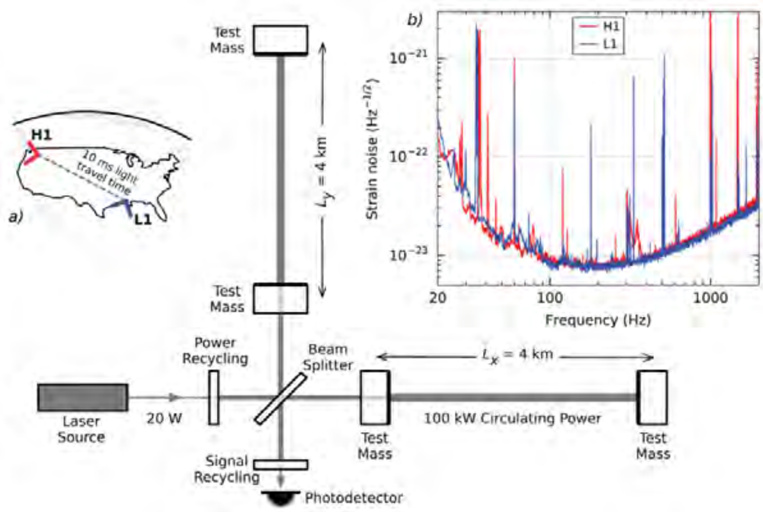


Figure 1: Simplified diagram of an Advanced LIGO detector (not to scale), also showing their position on the Earth's surface and the strain sensitivity curve as a function of frequency for both detectors.

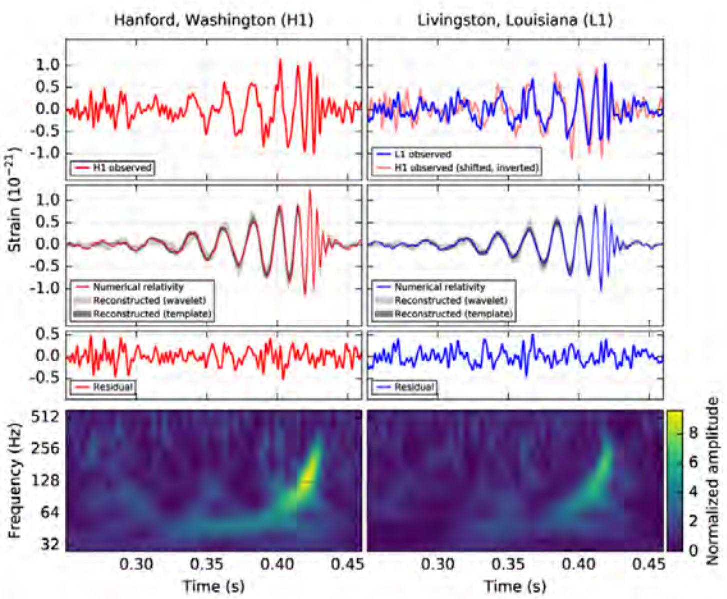
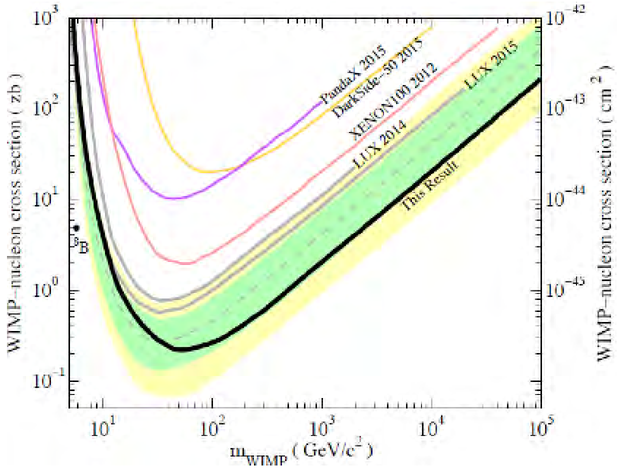


Figure 2: The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to 14th September 2015 at 09:50:45 UTC. Top row shows detected strain from each detector, filtered in a 35-350 Hz passband. The second row shows reconstructed waveforms with residuals, and the bottom row shows a time-frequency representation of the chirped signal.

Dark Matter Update

LUX



2016 has seen the final run of the Large Underground Xenon (LUX) experiment, based in the Sanford Underground Research Facility in South Dakota, USA. LUX is a dual-phase xenon time projection chamber (TPC) with a 250 kg xenon target, and has produced the most sensitive limits on spin-independent WIMP-nucleon scattering for intermediate and heavy WIMPs.

In July 2016 at the Identification of Dark Matter Conference in Sheffield, UK, LUX announced results from 332 new live days of data, which extended from September 2014 to May 2016 (Run 4). Their world-leading result cut into unprobed parameter space, excluding spin-independent Weakly Interacting Massive Particles (WIMPs) down to 2.2×10^{-46}cm^2 at the 90% confidence level for a 50 GeV/c^2 WIMP. This new result improved upon the LUX 2015 result by a factor of four at high WIMP masses. Since then the collaboration has released a combined Run 3 and Run 4 limit, strengthening this exclusion to 1.1×10^{-46}cm^2 at 50 GeV/c^2.

The fourth run was to provide the last WIMP search data for the LUX experiment. On 6th October, the detector was brought up out of its protective water tank and the lab is in the process of being cleared out and redeveloped to make way for the LUX-ZEPLIN (LZ) experiment, the successor of LUX, which will inhabit the same experimental hall. Some calibration data were taken by LUX after Run 4 as R&D for LZ.

Further analysis papers from the LUX data are expected over the coming months. Although built primarily as a dark matter detector, LUX can also be used to search for elusive processes including double electron capture and neutrinoless double beta decay of ^{134}Xe, as well as other particles such as axions and solar sterile neutrinos. Further dark matter searches will also be carried out including a search for inelastic dark matter and an inspection of the data for signs of annual modulation, so there is still plenty to come from LUX!

LUX-ZEPLIN

The LUX-ZEPLIN experiment is a dual-phase xenon time projection chamber dark matter search experiment that will contain ten tonnes of liquid xenon. The daughter of the LUX and ZEPLIN collaborations, LZ features over 200 scientists and engineers from across the USA, UK, Portugal, Russia and South Korea. The UK part of the collaboration includes researchers from Edinburgh University, Imperial College London, University College London, University of Liverpool, University of Oxford, University of Sheffield and STFC Rutherford Appleton Laboratories. LZ will scale-up the programmes from which it has grown, using demonstrated technology and extensive experience for a low-risk but aggressive dark matter search programme.

The project is presently well underway, with the procurement of the xenon, photomultiplier tubes, and construction of the cryostat vessels in progress. There is also an extensive quality assurance programme, in which elements of the final LZ design are currently being tested under liquid xenon and liquid argon.

A major landmark was achieved in August 2016 when LZ passed the "Critical Decision 2" milestone (in which the baseline for the experiment is defined) set by the US Department of Energy, one of the main funding bodies for the experiment. This cements a schedule in which underground installation of LZ will take place in 2019, with five years of operations planned to begin in April 2020.

DEAP-3600

DEAP-3600 is a single phase liquid argon dark matter experiment, located 2 km underground at SNOLAB, in Sudbury, Ontario, Canada. The collaboration is made up of around 65 researchers in Canada, the UK and Mexico. With one tonne of sensitive liquid argon, the target sensitivity to spin-independent scattering of 100 GeV/c^2 WIMPs is 10^{-46} cm^2. The detector is instrumented with 255 photomultiplier tubes and immersed in an 8 m tall water tank. Detector filling was recently officially completed. Data were taken continuously during the months of the fill, and it is anticipated that the results of the first physics run, which is still ongoing, will be published within a few months.

The DEAP-3600 background target is < 1 background event in the WIMP region of interest in three tonne-years. Strategies to achieve this include pulse shape discrimination, ultra-low radioactivity of detector construction materials and in-situ resurfacing of the acrylic vessel to remove radon daughters and other contaminants deposited during construction and fabrication. This resurfacing was completed in late 2014, leaving the vessel on the order of 100,000 times cleaner than the SNO neutrino experiment vessel! Analyses of these backgrounds have been very promising. The UK group within DEAP-3600 (at Royal Holloway University of London and University of Sussex) has been focussed on developing the calibration hardware, and this was all successfully installed at site. Data from calibrations using a laser ball has been used to tune the event reconstruction algorithm following the deployment of this hardware in summer 2015. The UK also has leadership in energy calibration and neutron calibration, and has developed the dark matter signal extraction software, as well as playing an active role in PMT charge calibration and event reconstruction.

Directional Dark Matter – DRIFT and CYGNUS at Boulby

It's been an interesting and challenging year for the directional dark matter community both in the UK and outside. The DRIFT-IId detector at Boulby successfully completed a tricky transfer from the old underground lab to the excellent new lab (see picture) along with the DRIFT-IIe vessel and gas systems. This was a tricky move but has resulted in a much better situation for the experiments.

DRIFT-IId has also been complemented by a completely new neutron shield, currently being put together, in which the former poly pellet shield around DRIFT-IId will be replaced by an arrangement of water filled blocks, currently being assembled underground. Meanwhile DRIFT-IIe, having been dormant for a while, has recently been turned into a test-bed for the wider CYGNUS directional effort. A CYGNUS proto-collaboration agreement was recently signed officially launching the international CYGNUS project. It involves scientists interested in gas and non-gas based technology and theory for directionality and includes an interest to look at the feasibility of a large TPC that could probe below the so-called neutrino floor in direct dark matter searches. This floor arises from coherent scattering of neutrinos from the Sun and atmosphere. Institutes involved in CYGNUS come from Australia, China, Europe, Japan and the US. First CYGNUS tests at Boulby involved a successful demonstration in December 2016 of a large area (50×50 cm) thick Gas Electron Multiplier (ThGEM) readout in CF_4 underground. Other significant milestones have been achieved by the DRIFT-IId, including a new sensitivity limit released and first demonstration that the direction sensitivity to the sense of recoil tracks (the so-called head-tail sensitivity) can be maintained, indeed improved, even in the new gas mixture currently adopted. This mixture is CS_2CF_4:O_2 and is an important step in the technology as it allows production of minority carriers in the gas such that full fiducialistion of the active volume can be achieved. This has allowed the experiment to run at zero-background. The next step with the work will be to establish operation of the Boulby CYGNUS test vessel with a full thick GEM array and to re-start fully shielded runs of DRIFT-IId to explore further the zero background operation. These efforts are becoming integrated into the wider CYGNUS network in which TPC experiments are being planed at the new Stawell underground site (Australia), in Kamioka (Japan) where funding has been received for a new 1 m^3 CYGNUS test facility and at Gran Sasso.

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Neutrinos

ANITA

ANtarctic Impulsive Transient Antenna (ANITA) is designed to search for ultra-high energy cosmogenic neutrinos using radio waves emitted via the Askaryan effect in the large volume of the Antarctic ice. The ANITA balloon stays around the continent at an altitude of 38 km, and more than a million km3 of ice is within view of the experiment. ANITA points its array of 48 quad ridge horn antennas at the ground below, scanning for vertically polarised impulsive radio signals, the signature of an ultra-high energy neutrino interaction.

ANITA-3 preparing for launch (photo from H. Schoorlemmer)

On 2014, an international team of scientists from the USA, Taiwan and the UK travelled to Antarctica to assemble and deploy the third flight (ANITA-3). ANITA-3 improved upon ANITA-2 in several ways, including an increased event rate and a GPU based program to quickly prioritise incoming events at a rate of at least 50 Hz. A limited satellite bandwidth means the flight computer can send one out of every thousand events back to the ground. The GPU will reconstruct the arrival direction of each event, together with a mean correlation value and implied power to prioritise each event. This algorithm was developed by a team at University College London. ANITA-3 also re-enabled triggers in the horizontally polarisation direction, after a set of horizontally polarised events in the ANITA-1 data set were discovered to be cosmic rays. Recovery of the full data set took some months and data analysis is still ongoing but will be finalised within the year.

At the same time the collaboration is gearing up for the launch of ANITA-4 in December 2016. ANITA-4 will feature a brand new trigger system and digitising electronics, allowing for lower energy thresholds and increased event rates.

IceCube/PINGU

Traditionally, Oxford is the only collaborator of IceCube. The future IceCube-Gen2 collaboration officially formed in 2015, and Manchester, Oxford, Queen Mary are among the founding members. The goals of IceCube-Gen2 are to extend its successful physics to both high-energy (10 km^3 array) and low-energy (PINGU) regimes. PINGU will use the higher density PMT arrays in the central region of IceCube to further reduce the energy threshold to reach the region where neutrino oscillations are sensitive to neutrino mass ordering. Intensive oscillation sensitive studies are ongoing by the PINGU analysis group led by the University of Manchester.

Super-Kamiokande/Hyper-Kamiokande

The year 2015 was a great year for the Japanese neutrino physics program, where they were awarded the Nobel prize (Super-Kamiokande) and three Breakthrough prizes (KamLAND, K2K/T2K, Super-Kamiokande). There are two more events that happened. Firstly, the Hyper-Kamiokande proto-Collaboration was officially formed, including 10 UK institutions. MOU of KEK and ICRR (institute of cosmic ray research) were made to further strengthen the collaboration. Secondly, the UK group (Imperial, Liverpool, Oxford, Queen Mary) joined the Super-Kamiokande collaboration. The UK group is working on the calibration, on top of various activities for the Hyper-K and Super-K gadolinium doping upgrade.

DUNE

The collaboration passed more than a few milestones in 2015. Firstly, the DOE CD-1 conceptual design report (CDR) review was completed. The conceptual design includes four 17.4 kilotonne (10 kilotonne fiducial volume) single phase liquid argon TPCs whilst retaining the possibility for dual phase TPCs. The CDR was signed by 12 UK institutions. The DUNE far detector prototype project (protoDUNE) has also been approved at CERN. There are two types of protoDUNE, single phase and dual phase (formerly known as WA105 of the LBNO prototype detector). Finally, the collaboration passed the DOE CD3a conventional facilities (CF) far site review. This is essential and allows the commencement of far site construction. The project is well on track to install the first far detector module in 2021.

Teppei Katori
Department of Physics, Queen Mary University London

Deep Science @ Boulby

News of the new underground laboratory at Boulby Mine to host the growing range of UK deep underground science studies.

In the last few days of 2016 finishing touches are being made to complete STFC's new deep underground science laboratory, 1.1 km below ground at Boulby mine in the North East of England. The facility provides 4000 m^3 of new, well-supported, class 10k and 1k clean room experimental space to support a wide range of UK-involved deep underground science projects from astroparticle physics (neutrino and dark matter studies) to studies of geology/geophysics, climate, the environment, and life in extreme environments on Earth and beyond.

Boulby Mine is a working Potash, Polyhalite and Salt mine in Redcar-and-Cleveland 30 mins south-east of Middlesbrough. At over 1.1 km deep, Boulby is the deepest mine in the UK and the 2nd deepest in Europe. Boulby has already been the focus of UK deep underground science for over 2 decades. The >1 km overburden means caverns at Boulby have a vastly reduced (by a factor ∼1 million) cosmic ray flux as compared to the surface of earth. This makes Boulby a "quiet place" to conduct low background projects for *e.g.*, dark matter searches and neutrino studies. Boulby is one of just a few such special sites in the world that enable such science. There are four such labs in Europe and little more than a handful worldwide.

Since the late 1980s many of the UK's dark matter searches have been conducted at Boulby; most notably the NAIAD, DRIFT and ZEPLIN dark matter programmes with the latter being the first working example of a 2-phase xenon dark matter detector. This is the technology now used in the world's most sensitive dark matter detectors. Boulby still hosts dark matter search studies including the DRIFT directional dark matter detector, and also operates a growing suite of world-class ultra-low background germanium detectors to be used for the screening of construction materials to be used in next-generation dark matter and neutrino experiments.

The science at Boulby has also been expanding; with teams from around the world realising that the low background and interesting geology at Boulby provides opportunities in a range of other areas. New studies at Boulby have included exploration of muon tomography techniques for deep structural monitoring in Carbon Capture and Storage (CCS) sites, studies of the effect of cosmic rays in aerosol formation and subsequent effects on climate, various studies of environmental radioactivity, and low background radio-dating.

At perhaps the furthest end from the original dark matter studies at Boulby, the facility has recently become the focus of astrobiology work. The layer of salt within which the Boulby caverns are mined has been found to be teaming with microbial life. Studies of this life is of great interest to those seeking to understand the limits of life on Earth and also the possibilities of life on other planets. With this connection, Boulby is now hosting the work of planetary exploration scientist from NASA and elsewhere with participating teams using the Boulby environment to test and develop instrumentation for future Mars rovers – including ESA's upcoming ExoMars rover which will use at least 2 instruments which have been tested at Boulby.

Science at Boulby is growing. Currently 9 studies are underway, involving over 70 external scientists from over 20 institutions and demand is growing. The facility is locally operated by a small STFC team, with much support from the local mining company (ICL-UK). It is an example of an immensely successful science and industry partnership. An issue in recent operations however has been that the laboratory that has been used in the last 15 years, the Palmer Laboratory: a 100m long laboratory <1 km walk from the central mine shaft, has been getting old, long-in-tooth, and no longer appropriate for use. Reacting to this; 18 months ago STFC provided funds (∼£1.8 million) to build a new laboratory to host current and future science for the next 2 decades and more. The resulting world class facility – the new underground lab on the block – is now all-but complete and ready for new studies.

For more information please contact the Boulby team at boulby@stfc.ac.uk. Please also connect via facebook (@BoulbyUndergroundLab) and twitter (@BoulbyLab).

Sean Paling
Boulby Underground Laboratory, Boulby Mine

The Cherenkov Telescope Array (CTA)

There have been many exciting developments in CTA since the last newsletter, beginning with the 2015 second-semester CTA collaboration meeting which was hosted by the University of Liverpool from 14-18 September 2015. The collaboration continues to grow, with, at present, nearly 1400 members from 32 countries. In the UK there are 57 CTA collaboration members from 13 institutes.

The CTA Observatory will have telescope arrays in two locations, one in the Northern Hemisphere and a larger one in the Southern Hemisphere, to provide all-sky coverage. Each site will host four large telescopes of 23m diameter, along with 12 (northern site) and 15 (southern site) medium telescopes of 12m diameter. The southern site will also host 70 small telescopes (4-m diameter) that will use three different designs. The small telescopes are equipped to capture the highest energy gamma rays, at energies in the TeV range and above, which emanate, for example, from the centre of our galaxy. That high-energy source is visible only from the Southern Hemisphere.

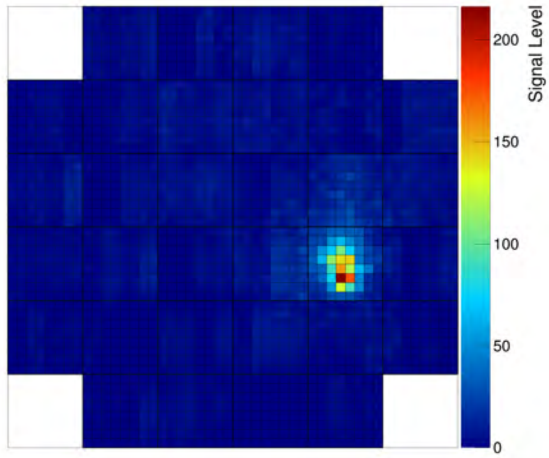
The UK has a major leadership role in the Gamma Cherenkov Telescope (GCT), one of the three Small-Sized-Telescope designs. Development of the GCT camera and mirror structures is underway at the universities of Durham, Leicester, Liverpool and Oxford, with funding from the Universities, STFC, and the EU. The telescope's novel Schwarzschild-Couder optical design also originated in the UK, and CTA-UK institutes are also involved in the development of CTA data analysis techniques. Professor Tim Greenshaw, of Liverpool University, is spokesperson for the GCT collaboration.

At the end of 2015, the GCT prototype recorded CTA's first ever Cherenkov light while undergoing testing at l'Observatoire de Paris in Meudon. During two weeks in November the GCT team battled poor weather to install and begin testing the GCT camera on the telescope structure in Paris. On the evening of Thursday, 26 November, they turned the telescope away from a nearly full moon and the bright lights of Paris towards a clear patch of sky. After 20 seconds, a single event triggered the camera, then another – in just over 300 seconds 12 events were captured. It was instantly clear that these were images of Cherenkov light images of air showers created in the atmosphere by cosmic rays. "This is a major milestone for the GCT and we hope for CTA." said Greenshaw. "Our design for the CTA telescopes that will detect the highest energy light hitting the earth's atmosphere from space has been proven to work; we are one step closer to developing a deeper understanding of where and how that light is produced."

GCT prototype, November 2015

It is planned for the first pre-production GCT telescope to be commissioned in mid-2018. "It's the science that's got everybody together, got everybody excited, and devoting so much of their time and energy to this," says Paula Chadwick of Durham University.

In June 2016, the CTA Observatory Council selected Bologna as the host site of the CTA Headquarters and Zeuthen, Berlin, for the Science Data Management Centre (SDMC) . The CTA Headquarters will be the central office responsible for the overall administration of Observatory operations. The SDMC will coordinate science operations and make CTA's science products available to the worldwide community. CTA is expected to generate approximately 100 petabytes of data by the year 2030.



Air shower image captured by the GCT. The field-of-view is eight degrees across and the event duration was about 5 ns.

CTA is on track for the first trial observations in 2021 and the first regular observations beginning in 2022. In September 2016, CTA Council concluded negotiations with the Instituto de Astrofisica de Canarias (IAC) to host CTA's northern hemisphere array at the Roque de los Muchachos Observatory in La Palma, Spain. CTA Council expects to complete negotiations with the European Southern Observatory before the end of 2016 to finalize plans for the southern array. The current plan is for a total of 99 telescopes in Chile.

The next few years will continue to be exciting as we perfect the systems for mass-production and then head to South America to commission the telescopes on site. But at that point, we will reap the ultimate reward: another new window on high-energy physics and astrophysics.

The CTA website is at `http://www.cta-observatory.org/`

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