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High energy astrophysics with the next generation of radio astronomy facilities

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High energy astrophysics has made good use of combined high energy (X-ray, γ-ray) and radio observations to uncover connections between outbursts, accretion, particle acceleration and kinetic feedback to the local ambient medium. In the field of microquasars the connections have been particularly important. However, radio astronomy has been relying on essentially the same facilities for the past ~ 25 years, whereas high-energy astrophysics, in particular space-based research, has had a series of newer and more powerful missions. In the next fifteen years this imbalance is set to be redressed, with a whole familiy of new radio facilities under development en route to the Square Kilometre Array (SKA) in the 2020s. In this brief review I will summarize these future prospects for radio astronomy, and focus on possibly the most exciting of the new facilities to be built in the next decade, the Low Frequency Array LOFAR, and its uses in high energy astrophysics.

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1. Introduction

High-energy astrophysics in general, and work on X-ray binary jets ('microquasars') in particular, has revealed important connections between radio and X-ray emission in astronomical objects. X-rays trace the instantaneous accretion rate, and radio emission the recent history of matter ejection, thereby allowing a measure of how much of the available accretion power is released in the form of radiation, and how much in kinetically-dominated flows (or even advected across an event horizon in the case of black holes).

In the early 1980s, when work on jets from X-ray binaries was first beginning (e.g. Hjellming et al. 1980), the radio community were commissioning a new and powerful facility, the Very Large Array (VLA). The X-ray community were analysing the exciting results from *Einstein* and looking forward to the imminent launch of EXOSAT, each of which pushed back the frontiers of X-ray astronomy. Nearly thirty years later, in 2008, the X-ray community can look back on an exciting three decades of new facilities, each (usually) more powerful than those which came before. In the radio world, however, the most powerful radio facility remains the VLA (very honourable mentions should of course be given to newcomers such as ATCA and GMRT). Fig 1 compares the arrival of new facilities in radio and X-ray astronomy over the past 40 years.

However, things are about to change. A worldwide renaissance in radio astronomy is planned, driven in large part by the (almost) united will of the global radio astronomy community to build the Square Kilometre Array (SKA, **www.skatelescope.org**), a 'transformational' wide-band world radio facility hopefully to be completed in the 2020s (see Hall 2005 and Carilli & Rawlings 2004 for engineering and science perspectives respectively).

2. Timeline for the radio renaissance

The first stage in this radio renaissance will come in the form of massive increases in the bandwidth of the VLA and MERLIN, resulting in order of magnitude increases in sensitivity, and the renaming of the facilities as EVLA and e-MERLIN ('e' is a generic term for upgrade / expansion / enhancement...). Both facilities are expected to be operational by 2010. EVLA will have slightly better instantaneous sensitivity and snapshot imaging, while e-MERLIN will have higher angular resolution at a given frequency. In addition, the Allen Telescope Array (ATA), is offering some open time for observations with its network of small, wide-field, dishes. It is also worth noting that we have already begun the era of real-time VLBI via the e-EVN and long baseline array in Australia.

In the overlapping period 2009–2011 three new facilities, which are rather unlike anything which came before, will begin to explore the low-frequency radio universe. LOFAR, the largest of these facilities, will operate in the 30–240 MHz range on baselines up to $\sim$ 1000 km. The Long-Wavelength Array (LWA) in the USA will operate similarly to the LOFAR low-band (30-80 MHz), whereas the Murchison Widefield Array (MWA) in Australia will operate in the LOFAR high band (80-240 MHz), but without the long baselines. LOFAR in particular is an extremely flexible instrument which is committed to a large fraction of open time, and will be discussed in more detail below.

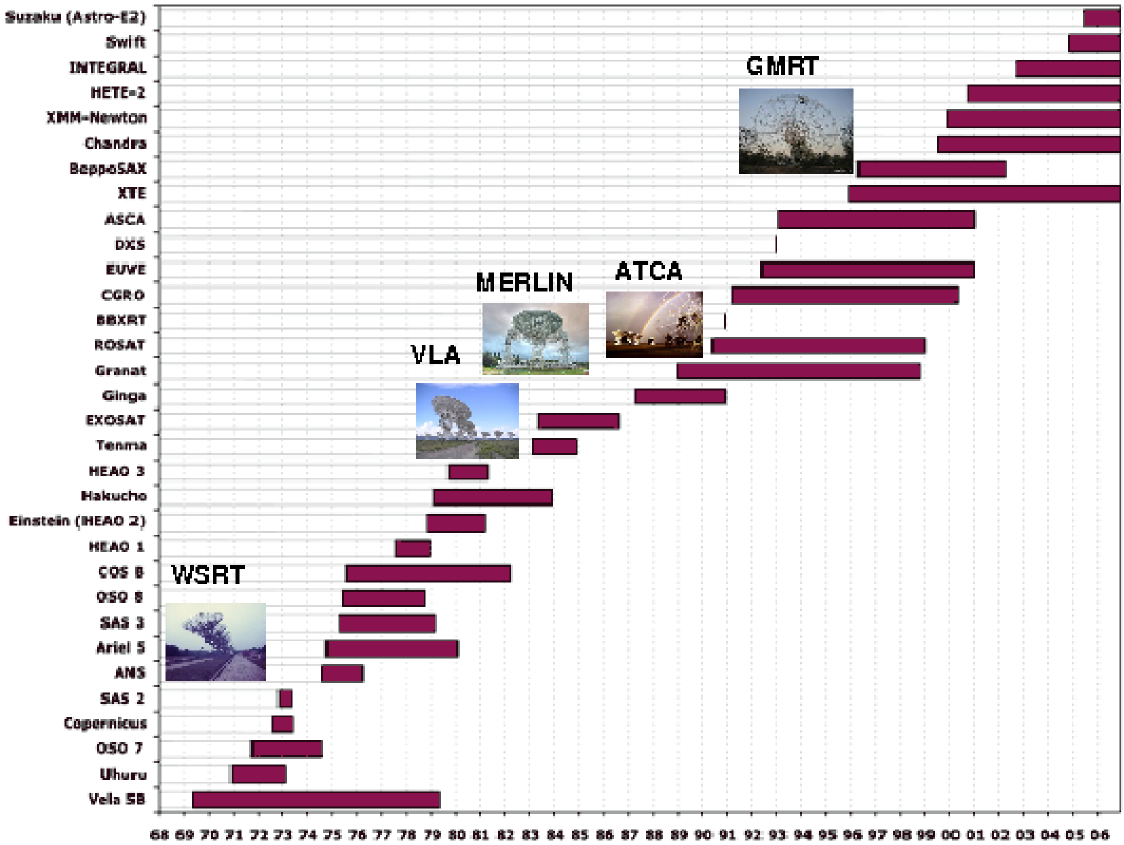

Figure 1: An illustration of the comparitive histories of new facilities in radio and X-ray astronomy since the 1970s. X-ray astronomy has had many more missions, most of which have limited lifetimes. Radio astronomy, on the other hand, is still largely using facilities and technology from the 1980s. I have not included in this figure VLBI arrays; note also that none of the indicated radio facilities have been decommissioned – are all still operating as open facilities today. The history of X-ray astronomy is from HEASARC (**http://heasarc.gsfc.nasa.gov/**).

On only a slightly longer timescale, the '1% SKA' pathfinders, MeerKAT in South Africa and the Australian SKA Pathfinder (ASKAP), will be constructed. These telescopes are likely to operate in the GHz range with conventional, albeit small, dishes, possibly with aperture arrays. Around the time that their construction is finished, the final site selection for the SKA is planned to take place, followed by a '10% SKA' pathfinder around 2015 and the final SKA by the early 2020s.

Over this period radio astronomy will have been revolutionized compared to the position it is now in. Raw sensitivity, fields of view and observing frequency range will all have increased dramatically. From the viewpoint of high-energy astrophysics this means daily monitoring of *all known active systems* will be trivial, and detection of new phenomena via all-sky monitoring at a wide range fo frequencies will be commonplace. It is useful to think of the many discoveries brought to high-energy astrophysics by, e.g. the All-Sky Monitor (ASM) onboard the RXTE satellite. However, the RXTE ASM can typically detect $\sim$ 500 sources per day; on a similar timescale LOFAR will monitor thousands of sources, and the final SKA and its pathfinders will be able to track the flux density variations of *millions* of sources every 24 hours.

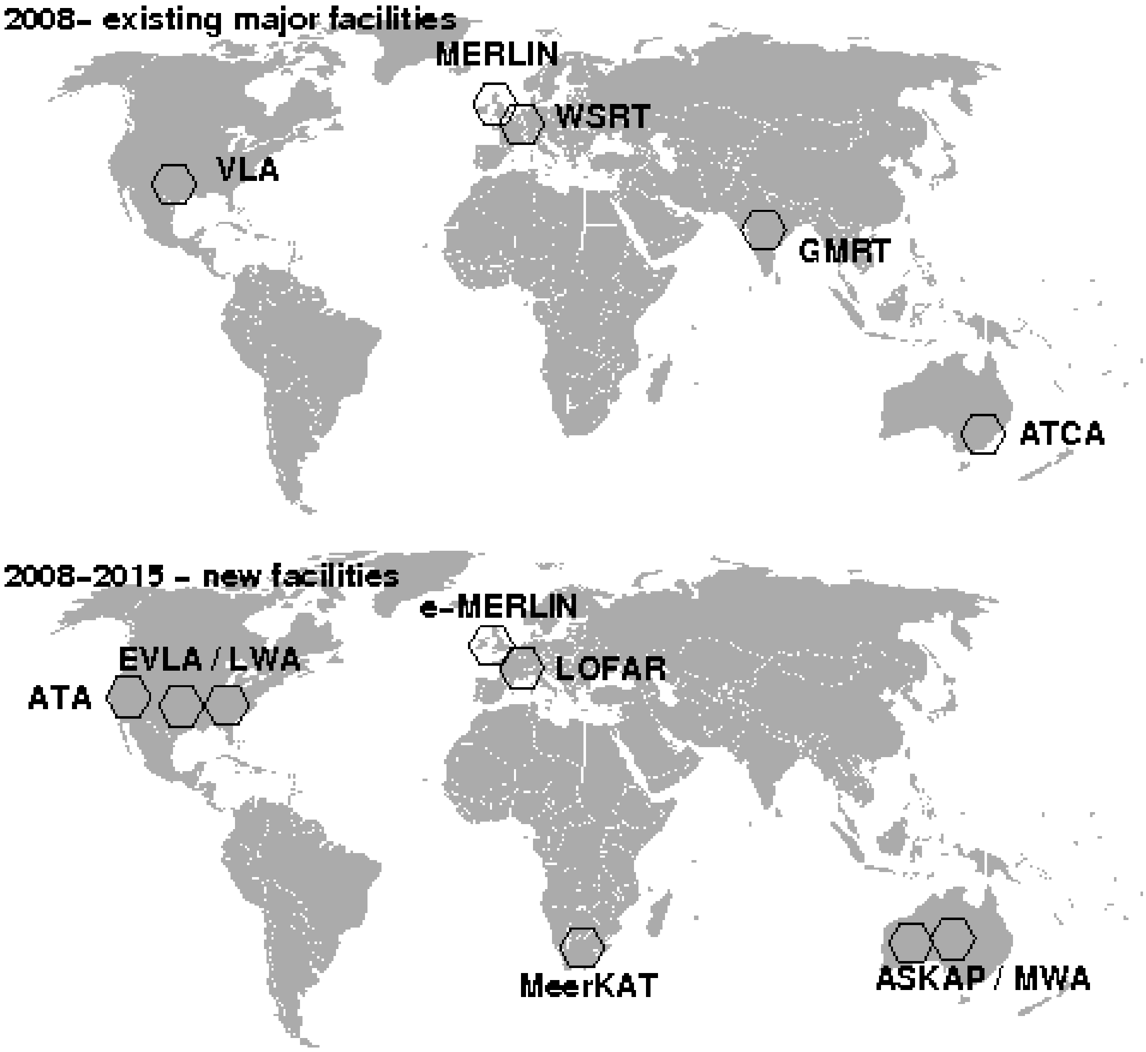

Figure 2: An illustration of the new radio facilities planned (and funded) within the next decade. The upper map shows the current major world astronomical facilities (I have deliberately not included VLBI networks, nor ALMA; apologies for other omissions). The lower map illustrates all those facilities anticipated prior to 2015. Beyond this timescale, the 10% and finally 100% SKA will be built in either Australia (ASKAP site) or South Africa (MeerKAT site).

3. LOFAR and high-energy astrophysics

One of the most exciting of the next-generation radio facilities for high-energy astrophysics, certainly in the next decade (and beyond), is LOFAR (**www.lofar.org**). LOFAR is a next-generation radio telescope under construction in The Netherlands with long-baseline stations under development in other European countries (currently Germany, The UK, France, Sweden). The array will operate in the 30–80 and 120–240 MHz bands (80–120 MHz being dominated by FM radio transmissions in northern Europe). The telescope is the flagship project for ASTRON, and is the largest of the pathfinders for the lowest-frequency component of the Square Kilometere Array (SKA). Core Station One (CS1; see Gunst et al. 2006) is currently operating, and the next stage of deployment

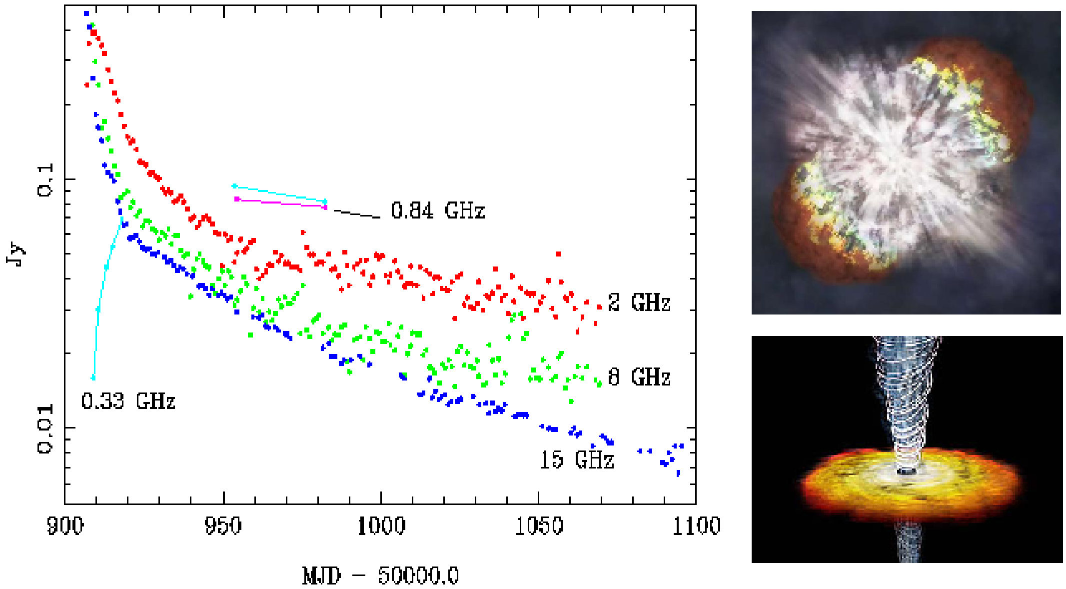

Figure 3: Evolution of a radio outburst from the X-ray transient CI Cam, with data from the Ryle Telescope (15 GHz), the Green Bank Interferometer (2 and 8 GHz) and the Westerbork Synthesis Radio Telescope (0.8 and 0.3 GHz). The radio signal is due to synchrotron emission from an expanding source of accelerated electrons. By the time of the first radio observations ('externally triggered' by X-ray observations) the radio source is already optically thin at the highest frequency, 15 GHz. As the source expands, the flux density at different frequencies increases as the optical depth at that frequency decreases, but then subsequently decays once in the optically thin regime as expansion results in energy losses. The emission at 330 MHz, just above the LOFAR band, was detectable within a few days of the outburst, but did not peak until 20–30 days later. Such behaviour will be characteristic of explosive outburst events associated with e.g. relativistic jets, supernovae, GRB afterglows (as indicated by the cartoons to the right of the figure), with the rise and decay timescales being an increasing function of the luminosity of the event.

is about to begin, with ~ 50 stations to be in the field by the end of 2010.

Most of the high-energy astrophysics research areas for LOFAR are associated with the *Transients* Key Science Project (KSP), one of six KSPs for the initial operations of LOFAR (the others being *The Epoch of Reionisation*, *Surveys*, *Cosmic rays / particle astrophysics*, *Solar / space weather* and *Cosmic Magnetism*). LOFAR is an exceptional instrument for such astrophysics because its enormous field of view coupled with multi-beam capability allows for the first time all-sky monitoring in the radio band, and because at such low frequencies it efficiently probes coherent radio emission processes very well for the first time. For more details see Fender et al. (2008).

3.1 A census of particle acceleration and kinetic feedback

Sychrotron radiation is a key signature of particle acceleration, which is in turn associated with the explosive injection of energy into magnetised media on all scales. Common examples include jets from X-ray binaries, Cataclysmic variables, Active Galactic Nuclei, and Young Stellar Objects, as well as Supernovae, Gamma-ray bursts and giant outbursts of Soft Gamma-Ray Repeaters. Fig 3 is a typical example of such an event, in this case for the outburst of a transient binary system which may contain a black hole.

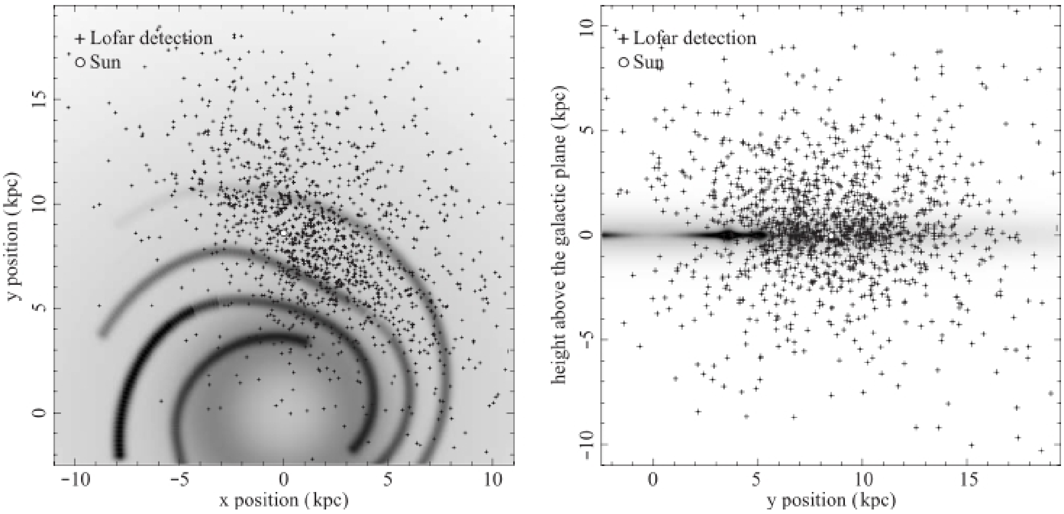

Figure 4: The 1000+ pulsars discovered in a 60-day LOFAR all-sky survey simulation. ISM shown in gray. Left) projected on the Galactic plane. Right) projected on the plane through the Galactic centre and sun, perpendicular to the disk. From van Leeuwen & Stappers (2008).

LOFAR has both advantages and disadvantages when it comes to observing such radio emission. On the plus side, its enormous field of view and the slow decay rate of synchrotron plasmas at the low LOFAR frequencies means that it will really be able to track the 3D distribution of particle acceleration in the local universe. On the negative side, as illustrated by Fig 3, it is not the ideal instrument for rapid triggering of events, as the synchrotron emission is typically initially self-absorbed at low frequencies and peaks in flux density much later than the originating explosive event (up to weeks in X-ray binaries or years in the case of supernovae or GRBs).

3.2 Pulsars surveys

LOFAR will undertake a major survey of classical radio pulsars as well as the study of related objects such as Anomalous X-ray Pulsars (AXPs) and Rotating Radio Transients (RRATs). The LOFAR pulsar survey is expected to discover more than 1000 new pulsars (see Fig 4), which will provide the majority of pulsars for the *Pulsar Timing Array* (Foster & Backer 1990) in the northern hemisphere. Such a survey also has a fair chance of turning up the first pulsar – black hole binary. In addition, LOFAR will provide the sensitivity to allow us to study the individual pulses from an unprecedented number of pulsars including millisecond pulsars and the bandwidth and frequency agility to study them over a wide range which will provide vital new input for models of pulsar emission. This will provide us with an unparalleled survey of the population of massive star end-products within our galaxy.

3.3 Extragalactic radio bursts

LOFAR may detect *extragalactic radio bursts*, such as that reported by Lorimer et al. (2007; Fig 5), to very large distances, possibly as far as $z \sim 7$, providing a unique probe of the properties of the intergalactic medium (via their dispersion, and possibly rotation, measure). Such events may be even be associated with neutron star–neutron star mergers, in which case the radio identification of

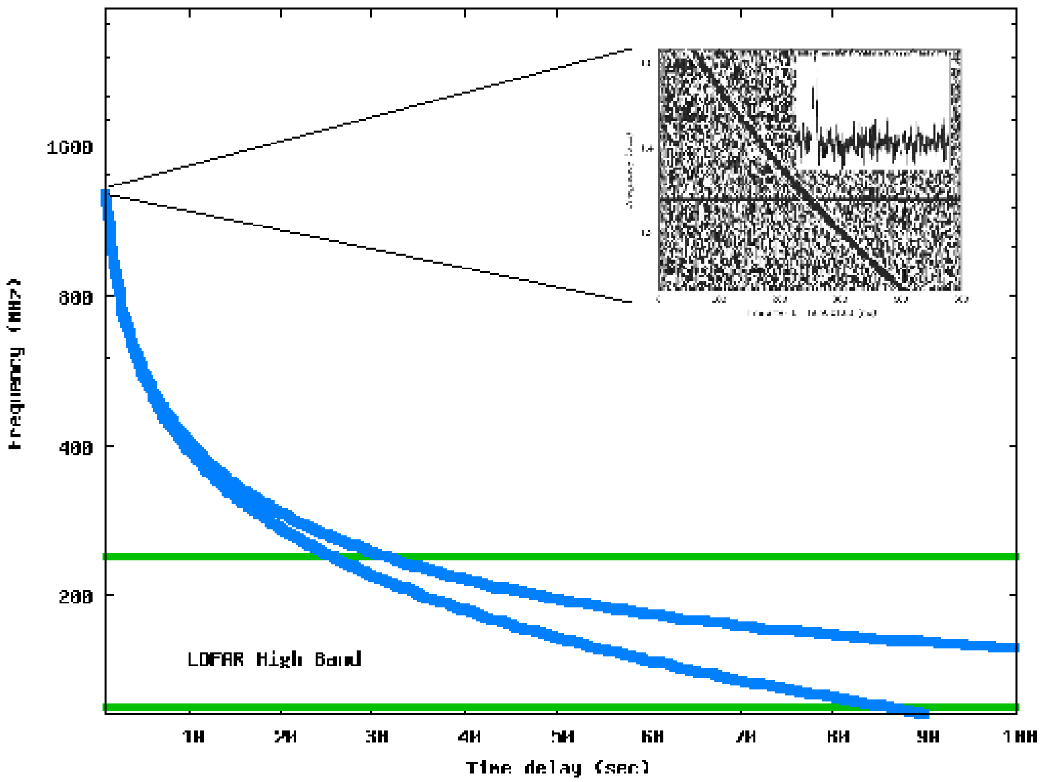

Figure 5: An illustration of how the highly-dispersed extragalactic radio burst reported by Lorimer et al. (2007) would sweep through the LOFAR high band (the frequency limits of which are indicated by the green horizontal lines) some tens of seconds later. The blue lines indicate the estimated delay and width of the pulse. The dispersion delay is assumed to be quadratic; the scatter-broadening of the signal is assumed to grow as ν^{-4} and we assume a pulse width of 5 ms at 1.4 GHz (note that the pulse was not resolved by Lorimer et al. and so this may be considered to be an *upper limit* to the scattered pulse width). If the measured steep spectrum ($S_\nu \propto \nu^{-4}$, the same as the scatter broadening) extends to low frequencies, such a burst would be detectable in the LOFAR standard data products up to distances in excess of a Gpc, allowing unprecedented studies of dispersion and scattering in the IGM. Such an event may even have been associated with a neutron star–neutron star merger. If so, such events may be detectable by LIGO, and a distance inferred from the gravitational wave signal alone. LOFAR identification of the host galaxy, via precise localisation of the burst, would allow two independent measurements of distance on cosmological scales, providing a unique test of gravity and of the distance–redshift relatio

events detectable by advanced LIGO may be possible. Since such mergers are predicted to provide independent distance measurements based on their gravitational wave signatures, identification of the electromagnetic counterpart would provide a unique test of gravity on cosmological scales, as well as an independent test of the redshift-distance relation.

3.4 Ultra high-energy neutrinos

LOFAR has already demonstrated its ability to detect radio bursts from cosmic ray airshowers, which is the main focus of the Cosmic Rays KSP. However, an even more exciting prospect (also part of the remit of that KSP) is the detection of radio Cerenkov bursts resulting from the interaction

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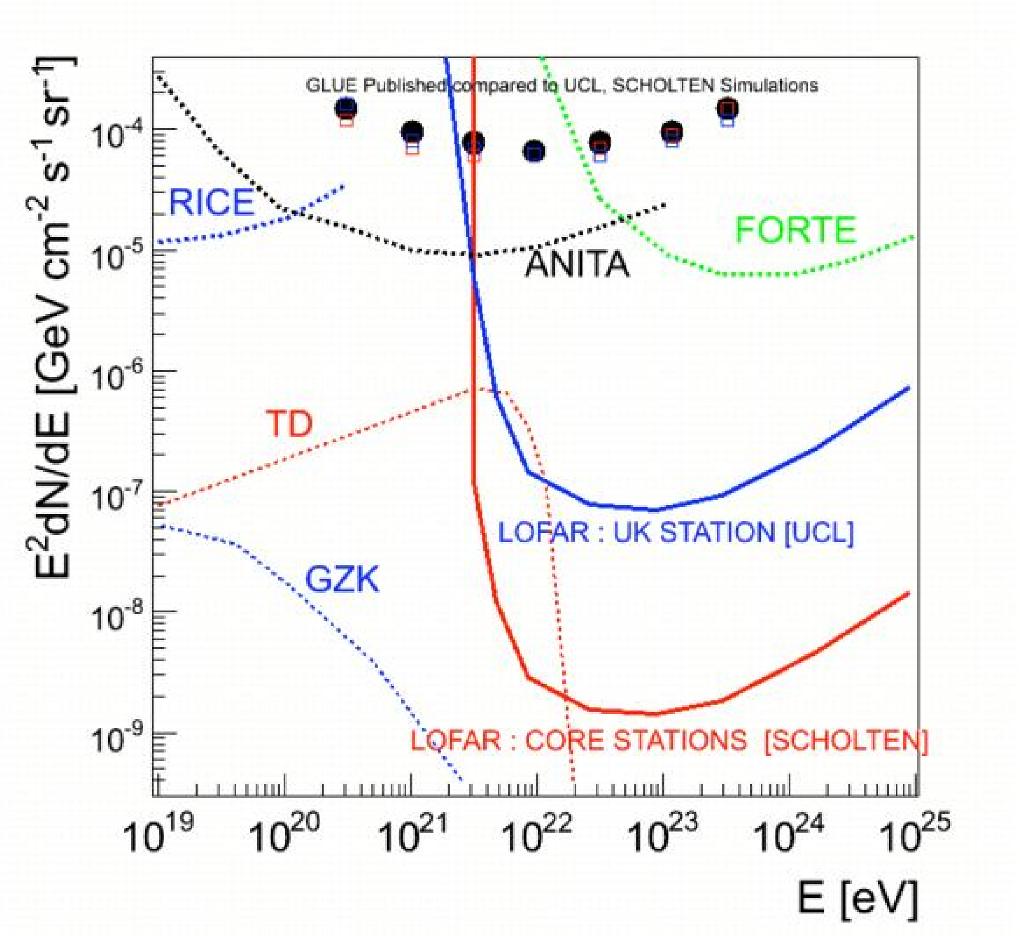

Figure 6: Published neutrino limits from RICE, ANITA, FORTE and GLUE compared to theoretical expectations from the GZK flux and a speculative 'new' physics source, Topological Defects (TD). LOFAR limits from the UCL simulation of a single UK station and the Scholten simulation of the core Dutch array are shown as the solid blue and red lines respectively. The predictions (UCL: open blue squares; Scholten: open red squares) of the two simulations are also compared to the published GLUE limits (closed black circles). Courtesy of Mark Lancaster, UCL.

of high-energy neutrinos with the moon, as predicted initially by Askaryan (1962). LOFAR is potentially the most sensitive instrument for this experiment (Scholten et al. 2006; see Connolly 2008 for a summary of other approaches), which could measure neutrino-nucleon interactions at a centre-of-mass energy exceeding the Large Hadron Collider by two orders of magnitude (see Fig. 6). Since the cosmogenic flux of such neutrinos (they are products of the Greisen-Zatsepin-Kuzmin process which causes the 'GZK cutoff' in cosmic ray energies) is predicted to be very low, such a detection would either imply 'new physics' such as topological defects, or a nearby strong source of high-energy neutrinos, both of which would be very exciting results.

4. Summary

High energy astrophysics has benefited greatly on multiple occasions by combining radio and

X-ray data. However, this process has taken place against a backdrop of ever improving X-ray facilities while the radio facilities have remained more or less constant in capabilities for more than two decades. All of this is about to change, with a whole host of new facilities coming on line in the near future which will not only deliver improved sensitivity, but revolutionize the way we do radio astronomy, for example allowing all-sky monitoring for transient and variable phenomena.

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