Boutiques & Experiments 2016

Radio Astronomy

Caltech Campus, July 21–23, 2016

Brassica olaracea var. *botrytis*

The stunning example of a brassica olaracea var. botrytis, or Romanesco broccoli, depicted on the cover exhibits numerous parallels with radio astronomy. The overall spiral arrangement of the florets immediately brings to mind the proposed configuration of SKA stations, and the increase in their sizes with radial distance is reminiscent of the log-periodic antenna. However, the fractal nature of the broccoli reminds us that objects of great beauty and complexity may exist even on bite-sized scales, and as pieces of larger objects, that are self-similar to the whole.

Preface

Boutiques & Experiments (B&E) is an invitational workshop. The purpose of this (hopefully durable) series is to examine carefully near-term opportunities in astronomy, especially for those areas which are expected to get or are getting vibrant. Last year we focused on optical synoptic surveys.[1] This year the workshop is focused on opportunities in meter-wave and cm-wave radio astronomy. In these bands astronomy is now both fecund and full of opportunities. As before, the workshop has an underlying contrarian flavor (in that the goal is to identify and harvest low-hanging fruits, especially ahead of future large projects).

To start with, Fast Radio Bursts (FRBs) continue to be puzzling but their diagnostic power to probe the IGM and intense sites of star-formation in other galaxies is unquestioned and supreme. A veritable industry (boutiques, experiments and large industrial machines), ranging from big facilities such as CHIME and Molonglo to small experiments such as DSA-10 at OVRO, centered around FRBs is now in full swing.

New centimeter- and meter-wave facilities are either producing or are on the verge of producing large amounts of data: LOFAR, ASKAP, MeerKAT, MWA and LWA (the list is not complete!). VLA is about to start a major sky survey (VLASS). In the US there is a low awareness of Spektr-RG (expected to launch next year). However this mission carrying eROSITA is like ROSAT on steroids. With its cadenced and synoptic all-sky coverage this mission is expected to revolutionize X-ray astronomy. The combination of of VLASS and SRG survey will be a bonanza for TDE science (at the very least). We are pleased that R. Sunyaev kindly agreed to attend the workshop and talk on Spektr-RG.

Next, we are officially in the era of GW astronomy. This is truly an exciting development. Stellar mass black holes exist in abundance, both singly and in binaries. In a curious way the LIGO discoveries offer hope that radio astronomers will soon discover a psr+bh system. Next, with regard to bh-ns and ns-ns coalescences, one could make a compelling case that radio observations will have as good a chance (and perhaps better than relative to other bands) of detecting long lived remnants.

Techniques have played an important and arguably critical role in the development of radio astronomy. For instance, the first generation of interferometers were designed to evenly sample the u-v space, whence their fully redundant East-West configuration (e.g. WSRT). The invention of the CLEAN technique opened up a dizzying number of array configurations (e.g. the VLA). A single algorithm had a profound effect on civil engineering requirements of radio interferometers! We have an entire session to discuss new algorithms, developments in signal processing (spurred by requirements of SETI and searches for FRBs) and community based common development (CASPER). On the more traditional analog hardware side the demonstration of cooled phased arrays (AO-19) is now opening up a new era in single dish astronomy (e.g. AO-40).

In the past, with considerable effort, joint surveys were undertaken (e.g. iPTF and VLA Stripe 82 survey). Thanks to the proliferation of optical synoptic surveys such initiatives can be expected to become routine (MeerLICHT calls for joint observations between MeerKAT and an optical wide field imager). In that spirit, discussions have started for a joint program between ZTF and SDSS (once both programs have finished their prime surveys).

We are following the same format as B&E 2015: have the proceedings available *ahead* of the workshop and expect the participants to read the extended abstracts (and the

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[1] `http://www.astro.caltech.edu/~srk/BnE2015Notes.pdf`

diligent student to read the suggested references) ahead of the workshop. The speakers are expected to entirely skip introduction and proceed directly to the heart of their talk. Chairs of all sessions have been instructed to ensure that there is 5 minutes of discussion for each talk.

An added attraction of B&E 2016 is that several radio astronomers who were heavily involved in the formulation and development of the VLA, VLBI & VLBA (B. Clark, M. Cohen, A. Readhead, & S. Weinreb) will be attending the meeting. It is a great pleasure to use this occasion to celebrate the ninetieth year of one of these astronomers (MC; page 67 of these proceedings). As with B&E 2015, we have included "historical" pictures but this time of radio astronomy facilities and personalities – in honor of the pioneering radio astronomers gracing this modest workshop. G. Hallinan took charge of this initiative and obtained vintage photographs from M. Cohen, A. Readhead and M. Goss, amongst others. We also have a fair number of young, novice and neophyte radio astronomers attending the workshop. In fact, all students who inquired or showed the slightest inclination were invited to attend the workshop. The workshop offers to be an intellectual treat and hopefully memorable to fans of radio astronomy.

I would like to thank D. Frail and G. Hallinan for helping me formulate the slate of speakers and invitees. Vikram Ravi was the editor for "B&E 2016 Notebook". As with B&E 2015, we are publishing the proceedings ahead of the workshop. This unusual[2] approach worked very well for B&E 2015. In addition, extended abstracts contributed by various attendees not giving presentations are also included in each section of the proceedings. The Caltech Optical Observatories provided the logistical and secretarial support for this workshop. Specifically, I would like to thank Bronagh Glaser who took care of much of the administrative burden and logistical chores for the workshop. I am grateful to Tony Readhead, Director of the Owens Valley Radio Observatory (OVRO), for partial support of this workshop.

S. R. Kulkarni

Pasadena
July 13, 2016

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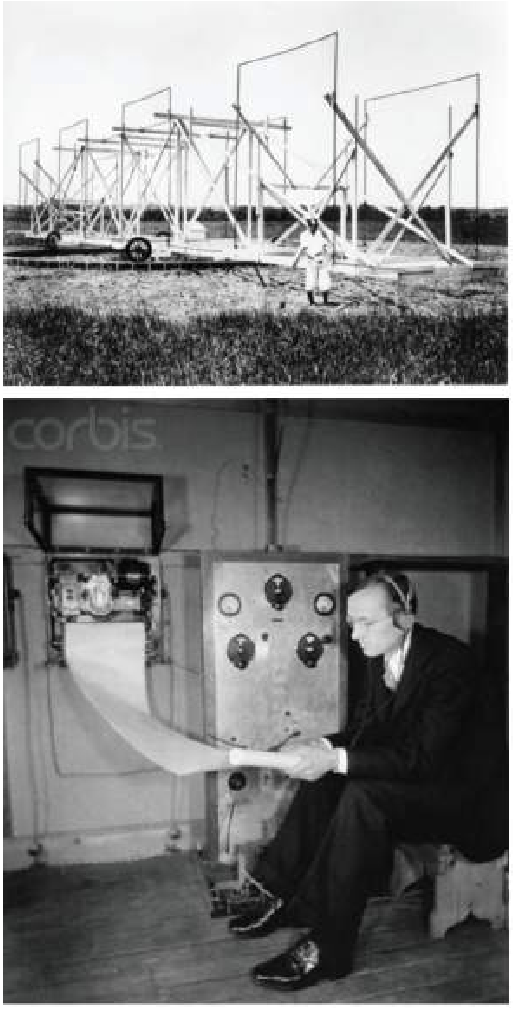
[2] In astronomy, proceedings are routinely published after the workshop and with delays of six months to a year. In computer science, the proceedings are published well ahead of the workshop. The latter is superior in that not only do the speakers come well prepared but so does the audience. The speakers can then directly proceed to their talk instead of starting off from Newton's *Principia* etc.



NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

The galactic radio waves, Mr. Jansky said, differ from the cosmic rays and also from the phenomenon of cosmic radiation, described last week before the American Philosophical Society at Philadelphia by Dr. Vesto M. Slipher, director of the Lowell Observatory at Flagstaff, Ariz.

Unlike the cosmic ray, which comes from all directions in space, does not vary with either the time of day or the time of the year, and may be either a photon or an electron, the galactic waves, Mr. Jansky pointed out, seem to come from a definite source in space, vary in intensity with the time of day and time of the year, and are distinctly electro-magnetic waves that can be picked up by a radio set.

New Waves Have High Frequency.

The cosmic radiation discovered by Dr. Slipher is a mysterious form of light apparently radiated independently of starlight, originating, Dr. Slipher concluded, at some distance above the earth's surface, and possibly produced by the earth's atmosphere.

The galactic radio waves, the announcement says, are short waves, 14.6 meters, at a frequency of about 20,000,000 cycles a second. The intensity of these waves is very low, so that a delicate apparatus is required for their detection.

Unlike most forms of radio disturbances, the report says, these newly found waves do not appear to be due to any terrestrial phenomena, but rather to come from some point far off in space—probably far beyond our solar system.

If these waves came from a terrestrial origin, it was reasoned, then they should have the same intensity all the year around. But their intensity varies regularly with the time of day and with the seasons, and they get much weaker when the earth, moving in its orbit, interposes itself between the radio receiver and the source.

A preliminary report, published in the Proceedings of the Institute of Radio Engineers last December, described studies which showed the presence of three separate groups of static: Static from local thunderstorms, static from distant thunderstorms, and a "steady hiss type static of unknown origin." Further studies this year determine the unknown origin of this third type to be from the direction of the centre of the Milky Way, the earth's own home galaxy.

Direction of Arrival Fixed.

The direction from which these waves arrive, the announcement asserts, has been determined by investigations carried on over a considerable period. Measurements of the horizontal component of the waves were taken on several days of each month for an entire year, and by an analysis of these readings at the end of the year their direction of arrival was disclosed.

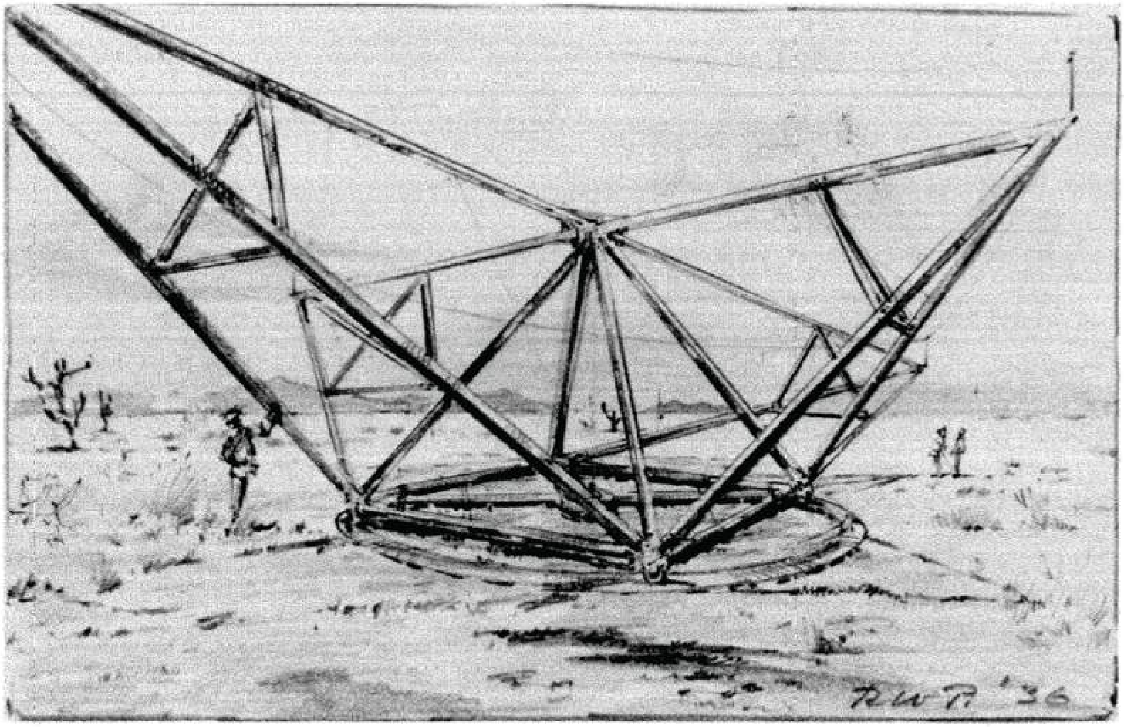
"The position indicated," it was explained, "is very near to the point where the plane in which the earth revolves around the sun crosses the centre of the Milky Way, and also to that point toward which the solar system is moving with respect to the other stars.

"Further verification of this direction is required, but the discovery, like that of the cosmic rays and of cosmic radiation, raises many cosmological questions of extreme interest."

There is no indication of any kind, Mr. Jansky replied to a question, that these galactic radio waves constitute some kind of interstellar signaling, or that they are the result of some form of intelligence striving for intra-galactic communication.

Radio Entertains the Children With Crime. Arthur Mann in May Scribner's.—Advt.

Karl Jansky of Bell Labs was assigned the task of investigating the sources of static that might interfere with shortwave radio voice transmissions. In 1933, he serendipitously achieved the first detection of astrophysical radio emission at a frequency of 20.5 MHz (14.5 m) with the confirmation of a source with sidereal motion in the apparent direction of the Galactic center. The result was published by Jansky as "Electrical disturbances apparently of extraterrestrial origin" in Proc. IRE (now IEEE) in 1933 and was widely publicized, appearing in the New York Times on May 5th, 1933. However, despite it becoming apparent that the radio emission could not be explained by astrophysical phenomena that were well understood at the time (e.g. Whipple & Greenstein 1937), it was not until the 1950s, and the development of the theory of synchrotron emission, that its true importance was realized.



In 1936, Gennady W. Potapenko, Professor of Physics at Caltech, together with graduate student Donald Folland, built an antenna in the Mojave desert that confirmed Janskys result. They campaigned for the construction of a much larger 90×180 *ft. rotating rhombic antenna (sketch above by R.W. Porter), but the request for* $\sim$ \$1000 *was rejected by Robert Millikan, ending any involvement in radio astronomy at Caltech for 20 years. Adapted from Cohen, M.H., 1994. The Owens Valley Radio Observatory: The early years. Engineering and Science (Caltech), 57(3), 8–23.*

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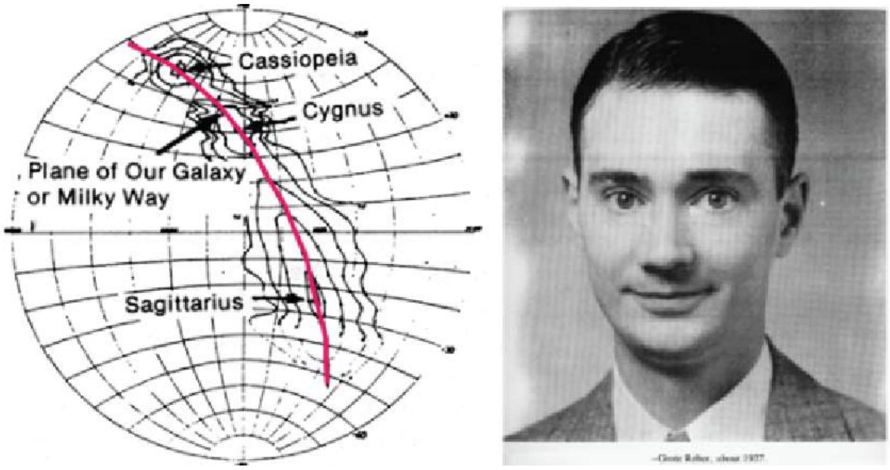
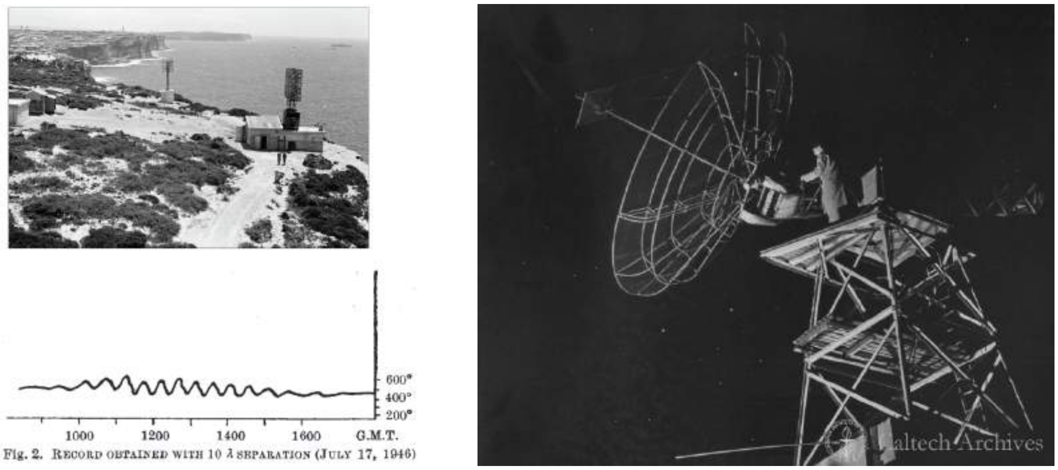
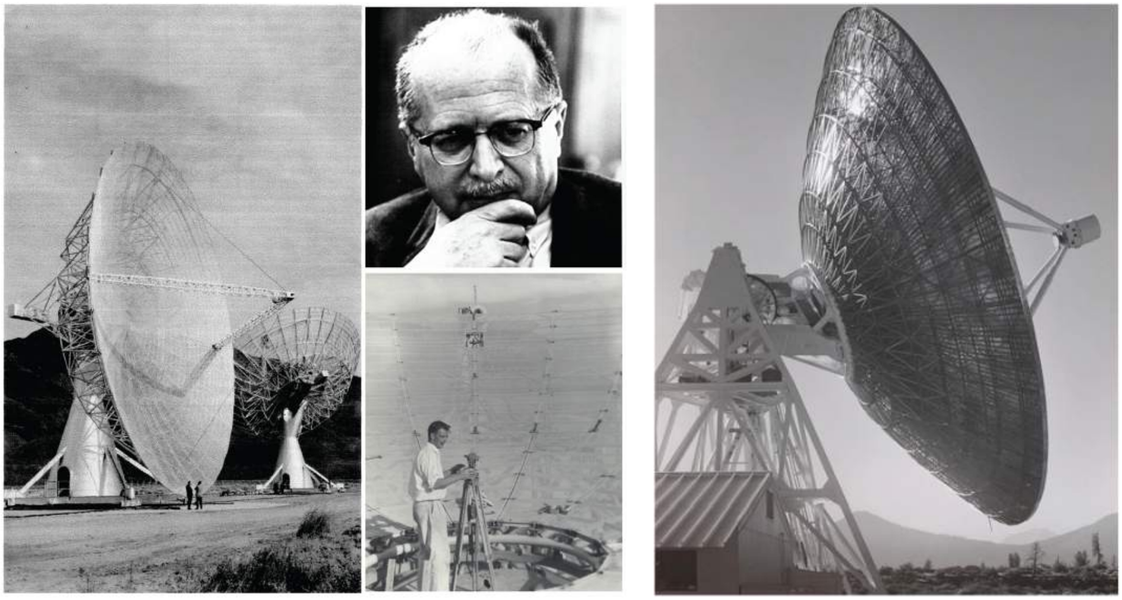


In 1937, motivated by Jansky's discovery, amateur astronomer Grote Reber built a parabolic dish of diameter 31.5 ft. in his back yard in Wheaton, Illinois. In the following years, Reber produced the first radio map of the sky based on a series of systematic observations at 160 MHz (left; resolution of $\sim 12^\circ$*) and 480 MHz. Reber tried to interest astronomers at Yerkes Observatory, but all showed little interest, except for a young Jesse Greenstein, who was faculty at the University of Chicago. Although Reber and Greenstein would go on to write the first review of radio astronomy in 1947, US involvement in radio astronomy was hampered by both skepticism and lack of interest from the wider community. With the growing importance after WWII of the radio astronomy contributions being made in Britain and Australia, Reber's pioneering studies ultimately became widely recognized.*



After WWII, radar engineers in the UK and Australia migrated into radio astronomy and begin developing the techniques that underpin modern radio interferometry. Prominent observatories were set up at Jodrell Bank and Cambridge (Ryle, Hewish, Lovell, Graham-Smith), and by the CSIRO Radiophysics Lab (then CSIR) in Australia (Bowen, Pawsey, Payne-Scott, Bolton, Mills, Christiansen, Stanley, Slee). Initial work was focused on solar emissions, but quickly progressed to the study of "radio stars", eventually established by Bolton et al. to be radio galaxies, paving the way for seminal, and often controversial work, on radio source counts, as well as the discovery of quasars. Radio astronomy in the Netherlands also began to grow rapidly, particularly after the detection of the 21-cm hydrogen line in 1951. Left: The Dover Heights field station in 1943, with fringes from observations of the Sun with a single-baseline interferometer from Ryle & Vonberg (1946). Right: Bolton operating a later version of the sea-cliff interferometer (1951; photo obtained from the Caltech Archives).



Motivated by the exceptional promise in associating radio and optical extragalactic sources, particularly the early discoveries relating to Cygnus A, Jesse Greenstein (top middle), now at Caltech, as well as Walter Baade and Rudolph Minkowski of Mt. Wilson, campaigned strongly for a radio astronomy program at Caltech. In parallel, Taffy Bowen , chief of the CSIRO radiophysics division, visited in 1951 and urged Caltech to set up a radio astronomy facility. Eventually Greenstein organized a conference in Washington in 1954 to discuss radio astronomy in the US, which proved to be a great success, simultaneously convincing Caltech president Lee DuBridge to invest in a radio observatory for Caltech, and stimulating the formation of the NRAO. Caltech convinced John Bolton and Gordon Stanley to move from Australia to Caltech to build a radio observatory, which eventually was sited in the Owens Valley. The first major construction effort resulted in the completion of two dishes in 1959, each of 90 ft. diameter, that together constituted the most powerful radio interferometer of its day (left). Bolton (bottom middle) often participated in construction of the antennas, and was known as an extremely skilful welder. This was to be great importance in the later localization of the quasar 3C273 at Parkes.
Right: The 85 ft. antenna at Hat Creek observatory was built in 1958 to study interstellar gas, and went to discover astrophysical masers (Weaver, Williams, Dieter & Lum, 1965). The telescope was used extensively in the 70s to map the Galactic H I. Numerous discoveries including the discovery of supershells came from these surveys.

Agenda

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SPEAKERS & Chairs:

Note 1: All but four talks are 20+5 minutes
        It is critical that discipline be maintained.
Note 2: Four talks, marked with "*", are 35+5 minutes


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July 21, 2016 (THURSDAY)
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1300-1310  Welcome, S. R. Kulkarni

Session A: Fast Radio Bursts, Chair: J. Kollmeier
1. 1310-1350*  A review of FRBs (+UTMOST), M. Bailes
2. 1350-1415   Searching for FRBs with the VLA, C. Law
3. 1415-1440   CHIME as an FRB machine, K. Vanderlinde
4. 1440-1505   DSA-10, V. Ravi
5. 1505-1530   APERTIF (slow & fast transients), J. van Leeuwen

   1530-1600   Coffee Break

Session B: Propagation,  Chair: J. Lazio
6. 1600-1625   Diffractive Scintillations & FRBs, J. Cordes
7. 1625-1650   Refractive Scintillations, K. Akiyama
8. 1650-1715   Extreme Scattering Events, K. Bannister
9. 1715-1740   Probing IGM, T. Akahori

1740-1900 Wine-n-Cheese Reception (Cahill Patio)

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July 22, 2016 (FRIDAY)
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   0800-0900  Continental breakfast

Session C:    GW, High-Energy & UV, Chair:  Y. Yatsu
10. 0830-0910* Spektr-RG Mission, R. Sunyaev
11. 0910-0935  MAXI, N. Kawaii
12. 0935-1000  ULTRASAT, E. Ofek
13. 1000-1025  GW+EM Astronomy, L. Wen

   1025-1100  BREAK

Session D: Relativistic Systems &  Explosions, Chair: J. Katz
14. 1100-1125  GHz radio transient sky in the GW era, K. Mooley
15. 1125-1150  Supernovae driven by Relativistic Engines, A. Corsi
16. 1150-1215  Galactic Double Neutron Star Systems, M. Kramer

   1215-1400  LUNCH a Cafeteria
              Before leaving for lunch participants self organize
              working groups to discuss topics such as
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- a. "RF/CASPER", Leader: S. Weinreb
- b. EM strategies in the GW era, Leaders: Kasliwal, Hallinan
- c. Phased arrays, J. Cordes
- d. After SDSS-4 (AS4), J. Kollmeier

The groups can continue the discussions next day during lunch

Session E: Transients, Chair: A. Horesh
17. 1400-1425 Transients: LOFAR, Carbone
18. 1425-1450 Transient: MWA, S. Croft
19. 1450-1515 Transients: LWA, Hallinan
20. 1515-1540 Status & Future of CASPER, D. Werthimer

1540-1610 BREAK

Session F: Transients II, Chair: B. Gaensler
21. 1610-1625 Galactic Radio Transients, G. Sivakoff
22. 1625-1650 Nuclear Radio Transients, K. Alexander
23. 1650-1700 Introducing Prof. Marshall Cohen, A. Readhead
24. 1700-1740* In Quest of High Angular Resolution: IPS, VLBI & Alfven Waves, M. Cohen

1745-1830 Reception (Atheneum Lawn)
1830-2030 Informal Dinner

July 23, 2016 (SATURDAY)

0800-0830 CONTINENTAL BREAKFAST

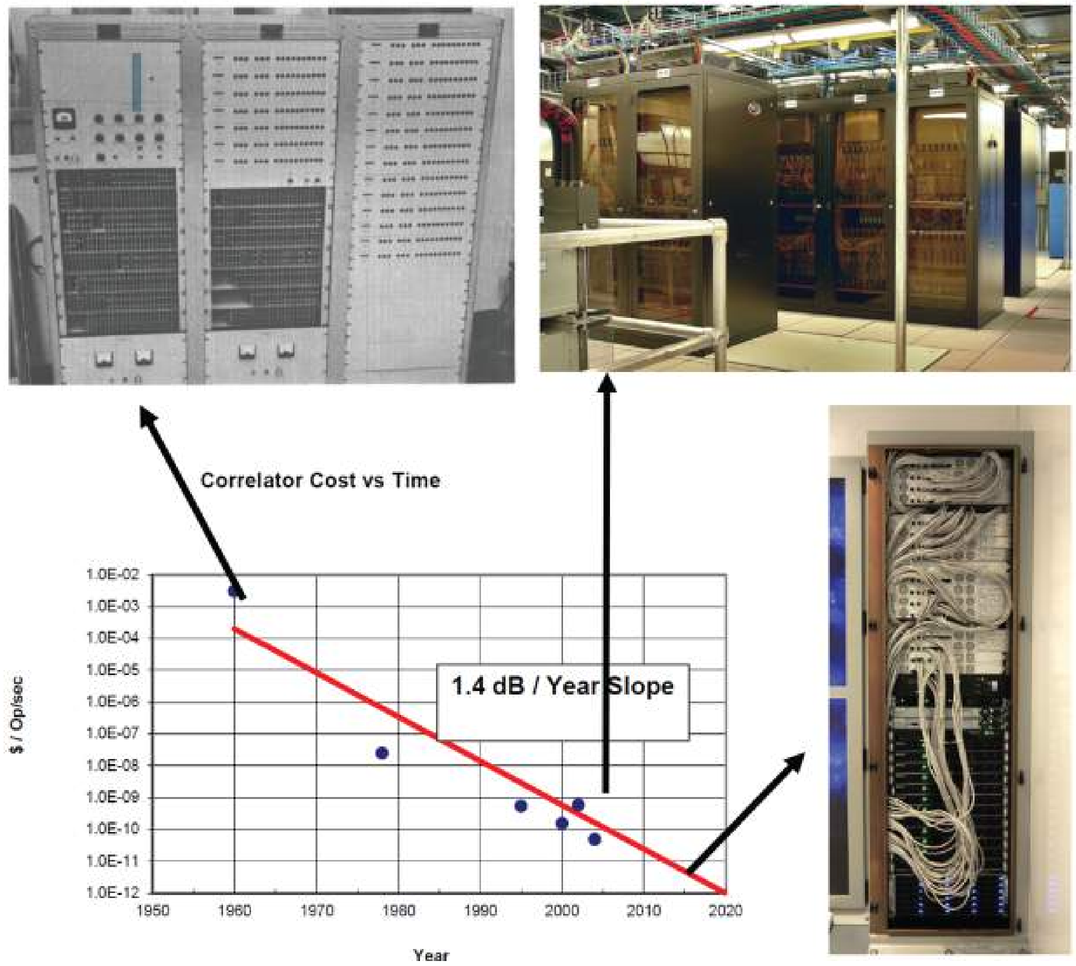
Session G: Methodology, Chair: B. Clark
25. 0830-0855 Breakthrough Listen, D. Price
26. 0855-0920 VLASS: On-The-Fly Mapping & Rapid Data Products, S. Myers
27. 0920-0945 MeerLICHT (& MeerKAT), P. Groot
28. 0945-1005 Breakthrough Algorithms, B. Zackay
29. 1005-1030 Real time transient detection, J. Hessels

1030-1100 COFFEE BREAK

Session H: Radio Boutiques & Experiments, Chair: J. Lazio
30. 1100-1125 Tests of GR with satellite tracking, D. Duev
31. 1125-1150 Wideband Monitoring of radio sources, H. Vedantham
32. 1150-1215 Single dish & VLBI in Japan, K. Fujisawa
33. 1215-1255* The eco-system of Radio Observatories: Boutiques & Behemoths, D. Frail

1300 Working Lunch in the patio area (Box lunches will be provided; please sign up)
The discussions started the previous day will continue. To recap:
- a. Common development for RF, fibers, LNAs, led by Weinreb
- b. Radio & Optical in GW era, led by M. Kasliwal & G. Hallinan
- c. Status of Phased Array Feeds, led by J. Cordes
- d. After SDSS-4 (AS$), led by J. Kollmeir

Above: By the 1960s, support was building for expanded radio facilities at OVRO. Led by Gordon Stanley (top left), acting director of OVRO after the departure of John Bolton for the construction of the Parkes 64 m dish, funding was secured in 1963 for a prototype antenna, of 40 m diameter (shown under construction at bottom). This antenna has been used extensively ever since, primarily for VLBI. The 40 m antenna is currently employed in a program led by Tony Readhead, monitoring $>$ 1700 *blazars on a near continuous basis. Top right: John Bolton, Al Moffett and Bruce Rule in attendance at the dedication of the 40 m dish. Below: Evidence from the 2013 Hollywood movie Superman: Man of Steel suggests a continued expansion of the OVRO facilities, at least some alternate timelines. Superman is the caped individual on the left side of this image, beside the wreckage of a downed missile that was likely a source of RFI for the site.*



Top left: The first radio astronomy digital correlator was built by Sandy Weinreb in 1960. Top right: The WIDAR correlator of the Jansky VLA, a state of the art instrument that initiated full operations in 2010. Bottom right: The LEDA correlator (Kocz et al. 2015) consisting of CASPER ROACH2 boards and Nvidia GPUs, an example of a new generation of correlators using commercial hardware for rapid design and low cost. Bottom left: The cost of radio astronomy correlators, as expressed in OPS/\$/s, has decreased by ~ 10 *orders of magnitude in 50 years [adapted from Sandy Weinreb].*

Session A: Fast Radio Bursts

Talks

A1. A review of fast radio bursts and the UTMOST project (Matthew Bailes)

A2. Searching for FRBs with the VLA (Casey Law)

A3. CHIME as an FRB machine (Keith Vanderlinde)

A4. Deep Synoptic Array prototype for FRB localization (Vikram Ravi)

A5. Transients with APERTIF (Joeri van Leeuwen)

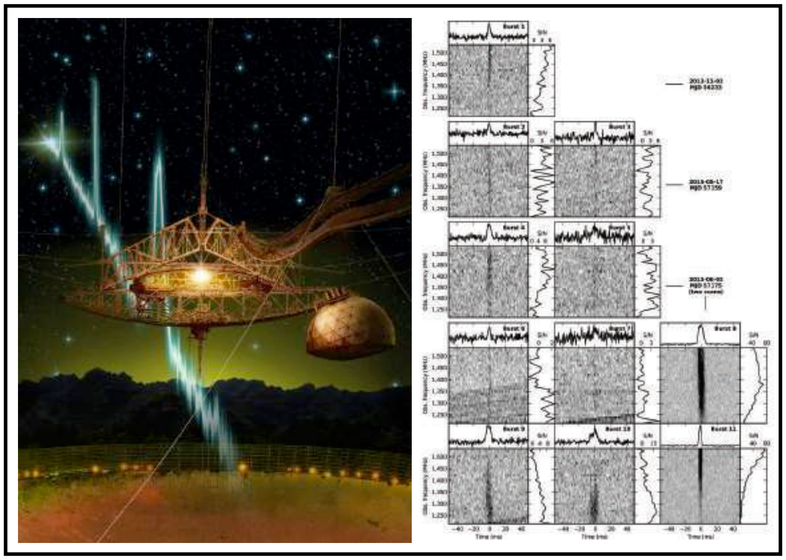
Contributed abstracts

A6. A search for FRBs with the GBNCC survey (Pragya Chawla)

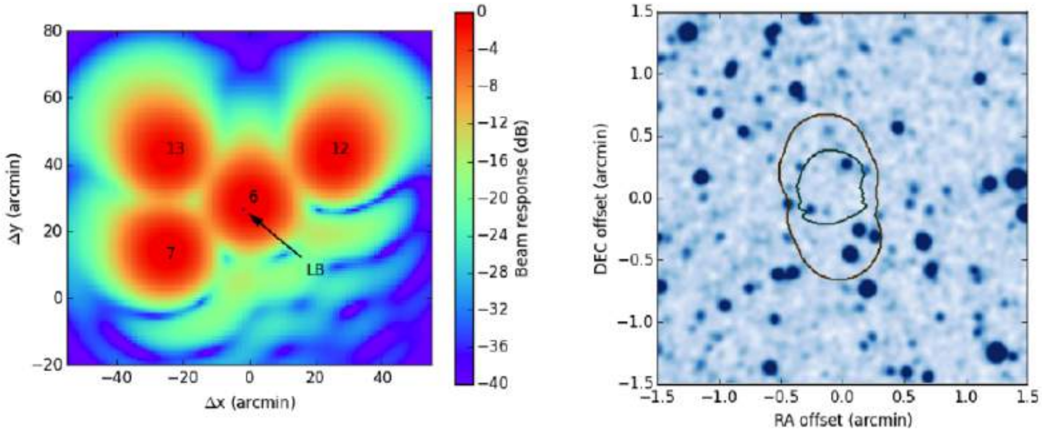
A7. FRB: PSR, SGR, ? (Jonathan Katz)

A8. Magnetar giant flares and Galactic FRBs (Shriharsh Tendulkar)

A9. Monitoring pulsars and the ISM with CHIME (Shriharsh Tendulkar)



Left: The 305-m Arecibo telescope and its suspended support platform of radio receivers is shown amid a starry night. From space, a sequence of millisecond-duration radio flashes (fast radio bursts; FRBs) are racing towards the dish, where they will be reflected and detected by the radio receivers. Though this is an artists conception, the bursts shown here are derived directly from the real data presented by Spitler et al. (2016, Nature, 531, 202). Figure Credit: Danielle Futselaar. Right: Dynamic spectra (frequency vs. time) and band-averaged emission for the first 11 bursts detected from FRB 121102. Figure supplied by J. Hessels.



Localization of the Lorimer burst (D. Lorimer et al. 2007, Science, 318, 777) – the first and brightest FRB detected to date – using its detections in four beams of the 21 cm Parkes multibeam receiver (response patterns on left). Figure supplied by V. Ravi.

A Review of Fast Radio Bursts and the UTMOST Project

Matthew Bailes
Centre for Astrophysics and Supercomputing, ARC Centre of Excellence for All-sky Astrophysics (CAASTRO)
Swinburne University of Technology

The first radio pulsars discovered (Hewish et al. 1968) were bright radio sources with long rotation periods in which individual pulses were visible. They were detectable because their pulsed emission repeated regularly, allowing them to be distinguishable from the multitude of solitary bursts of radio emission that are produced by man-made interference. It soon became apparent that weaker and faster pulsars could be discovered by performing long integrations and searching multi-channel datasets in dispersion measure (DM) using the fourier transform. One of the first searches to employ these techniques discovered the celebrated binary pulsar PSR B1913+16 (Hulse and Taylor 1975). Over the subsequent almost five decades pulsar surveys have made tremendous advances, resulting in the discovery of over 2500 radio pulsars, using finer and finer frequency and time resolution. The known pulsars now span periods of 1.4 milliseconds to over 8 seconds.

In 2006 McLaughlin et al. (2006) made a pioneering breakthrough when instead of searching for pulsars with the Fast Fourier Transform (FFT), they looked for individual dispersed pulses. A new population of neutron stars were thus uncovered, the so-called RRATs, pulsars that only pulse rarely and in some circumstances have better signal-to-noise ratios in individual pulses than in the FFT. This motivated Lorimer et al. to search other archival datasets for more RRATs, and in a search of the outer reaches of the 2001 Parkes 64-m Small Magellanic Cloud survey of Manchester et al. (2006) his team uncovered the celebrated "Lorimer burst" (Lorimer et al. 2007) (hereafter the LB). The LB exhibited the precise pulse dispersion and scattering relations expected of extra-terrestrial source, but possessed a dispersion measure (375 pc cm^{-3}) that inferred that it was extragalactic in origin. It was so bright that it appeared in multiple beams of the Parkes multibeam receiver causing the 1-bit digitizer to saturate in the beam closest to the source. The peak flux (~30 Jy) and fluence (~150 Jy-ms) was far in excess of the Parkes single pulse detection threshold and its profound brightness raised many disturbing issues.

The first issue was that the LB was so bright we should see other fainter examples, and the second was that the implied luminosity was far in excess of any pulsar or RRAT-like emission ever witnessed. Early attempts to find other examples of the LB in either archival data, or in new surveys failed (eg Siemion et al. 2012). When Burke-Spolaor et al. (2011) discovered an obviously terrestrial population of dispersed radio emission in other surveys (the "Perytons") conducted by the Parkes telescope near the dispersion measure of the LB, confidence in the extraterrestrial nature of the LB faltered.

Keane et al. (2012) reported the discovery of a solitary burst of radio emission in the galactic plane with a DM of 746 pc cm^{-3} some 30% higher than the "maximum" dispersion predicted by the ne2001 free electron model of Cordes & Lazio (2002) but Bannister & Madsen (2014) have since argued that the dispersion in this direction is higher than ne2001 suggests and that the burst is therefore a galactic RRAT, although it has never been seen to repeat.

The first large-scale survey (hilat) of high galactic latitudes at 20cm wavelengths to employ digital filters was conducted as part of the High Time Resolution Universe (HTRU) surveys (Keith et al. 2010) with the Parkes 64-m telescope. Digital filters offer the opportunity to greatly reduce the deleterious effects of pulse dispersion, and the hilat survey commenced in 2011 and was searched for pulsars and Lorimer bursts. The survey used the 13-beam multibeam receiver, and this enabled advanced eigenvector decomposition techniques (Kocz et al. 2012) to remove interference. The results of this survey were transformational for extragalactic radio bursts.

In Thornton et al. (2013) four new examples of dispersed radio emission were presented, including a 50-sigma event with a perfect dispersion sweep that displayed a pulse width as a function of frequency consistent with that expected from scattering. Thornton et al. suggested that these radio pulses were from the same population as the LB and that they be called the Fast Radio Bursts, or FRBs with their UT day of the event following the FRB acronym. The Lorimer burst therefore became FRB 010724.

Once the Thornton results were presented there was renewed effort in searches for FRBs out to even greater DMs in new and archival surveys. Burke-Spolaor & Bannister (2014) found an FRB in the Parkes intermediate latitude survey (Jacoby et al. 2009) although other searches of large-scale surveys failed to detect FRBs (eg Petroff et al. 2014, Rane et al. 2016). It remained concerning that the only instrument to ever detect an FRB was the Parkes telescope.

Kulkarni et al. (2014) explored whether it was possible to unite the LB, Perytons and the FRBs into one unified model in which all originated from an atmospheric phenomenon, in part motivated by the lack of a plausible model for the implied FRB luminosities and event rates. Their abstract concluded by urging astronomers to do two things:

> *First, the detection of a single FRB by an interferometer with a kilometer (or longer) baseline will prove that FRBs are of extraterrestrial origin. Second, we urge astronomers to pursue observations and understanding of Perytons since they form (at least) a formidable foreground for the FRBs.*

Confidence in the FRB phenomenon grew when FRB 121102 was discovered at the Arecibo 305-m dish by Spitler et al. (2014) and many others at the Parkes telescope (Petroff et al. 2015, Ravi et al. 2015, Champion et al. 2016) with DMs up to 1600 pc cm^{-3}. The first FRB to be detected at the Green Bank Telescope was discovered at 800 MHz, and exhibited a large rotation measure of -186 rad m^{-2} (Masui et al. 2015). In another important breakthrough Petroff et al. (2015) discovered that the microwave ovens at the Parkes site were the source of the Perytons and it appeared to be possible to separate the Perytons from genuine FRBs-satisfying the first of Kulkarni et al.'s pleas to the community. In a recent dramatic development, Spitler et al. (2016) discovered that FRB 121102 repeated and could be seen by both Arecibo and the GBT establishing beyond any doubt that at least FRB 121102 was not a terrestrial phenomenon. For a summary of all known FRBs see the online FRB catalogue by Petroff et al. (2016) http://www.astronomy.swin.edu.au/pulsar/frbcat/. Keane et al. (2016) recently published a putative FRB host galaxy location based upon temporally-coincident flaring near an AGN but the confidence in this association has been called into question (Williams & Berger 2016, Vedantham et al. 2016).

To me the main issues with FRBs today are:

- Are all FRBs produced by the same mechanism and objects? Is there one class or more? Do they all repeat?
- Are the FRB DMs dominated by the contribution of the intergalactic medium, or by material in the host galaxy?
- If FRBs are at cosmological distances, can we establish their host galaxies and use them as cosmological probes?

Shortly after the discovery of the Thornton bursts we began exploring whether the old Molonglo Observatory Synthesis telescope could be an efficient FRB detector? We designed modifications to the SKAMP-2 prototype that included the deployment of a large number of servers with inexpensive Graphics Processing Units (GPUs) to turn the 18,000 m^2 interferometer into a 24x7 FRB detector known as the "UTMOST". The parabolic cylinder is comprised of 352 4.7m x 11.7m ~ 50 m^2 sections (modules) that have a ~8 square degree field of view. We form 352 fan-beams across the primary beam and search in dispersion space for FRBs in real time. At the time of writing the back-end system is 100% operational, although system performance varies greatly between the modules. The UTMOST has the advantage that near-field objects should appear in 1-2 adjacent fan-beams and that local sources of interference will be out of focus and easy to discern from genuine celestial events.

The UTMOST receivers sample 31.25 MHz of bandwidth from 820 MHz to 851.25 MHz in 40 x 781 kHz channels in just one right-circularly polarized radio frequency input – see Caleb et al. (2016).

At the time of writing the UTMOST has detected three events that are consistent with FRBs with DMs ranging from ~300 to ~1150 pc cm^{-3}. Two of the FRBs are clearly visible in two adjacent fan-beams, and entirely consistent with extra-terrestrial emission far beyond the telescope's Fresnel zone of in excess of over 6,000 km. All three of the FRBs have widths consistent with their dispersion measure smearing width from the initial polyphase filterbank. The detection of these events with an interferometer, in conjunction with the repeating FRB would appear to establish beyond all doubt that FRBs are an extraterrestrial phenomenon that pose many interesting questions. New instruments like CHIME should mean the FRB discovery rate continues to increase in the near future.

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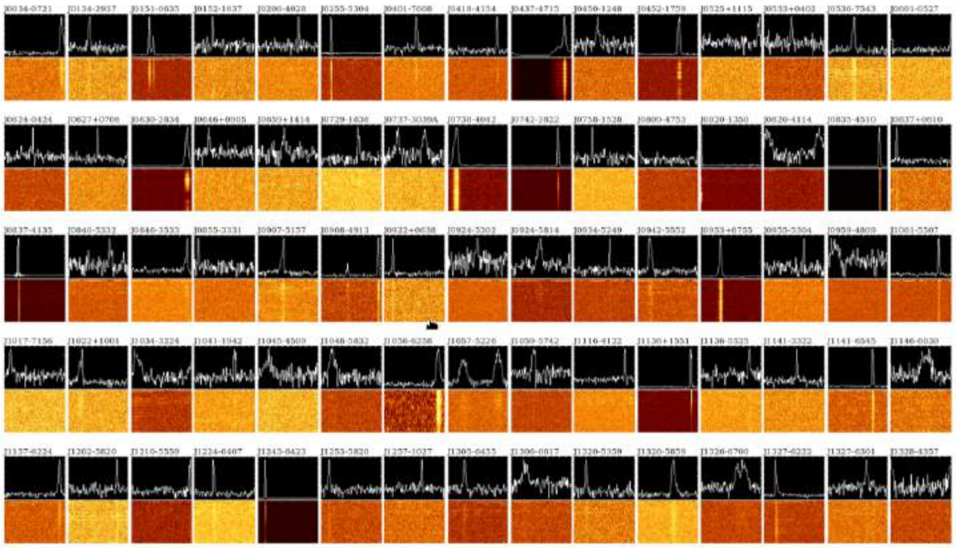
View of the Molonglo valley site near Hoskinstown, NSW, Australia, showing the UTMOST telescope reflector surface and feed line.



Examples of pulsar observations with UTMOST in both transiting and tracking tied-array modes. The two-dimensional plots depict the pulsar flux density vs time.

Notes

Searching for FRBs with the VLA

Casey J. Law

The field of Fast Radio Bursts (FRBs) is now nearly a decade old and in the last year saw the publication of three high profile papers. But the earliest and most basic questions raised about FRBs remain unanswered: What are they and how can we use them?

Two broad classes of models have emerged to explain FRBs. Either their progenitors reside at cosmological ($z \sim 1$) distances and their dispersion traces the intergalactic medium or they come from relatively nearby (<100 Mpc) galaxies and their dispersion largely traces their environment. Existing single-dish observations localize to arcminute scale, which is too poor to identify arcsecond-scale optical/IR counterparts that would resolve this question.

We have pioneered a series of technical developments for "fast imaging" of radio transients at the Jansky Very Large Array (VLA). Interferometers can precisely localize and efficiently survey for FRBs, but doing so requires producing millisecond-scale visibility data, managing a TB hr^{-1} data stream, and new data analysis software. To do this, we developed "rtpipe"[1], a Python library for radio interferometric transient searches with CPU clusters. This library has accomplished peak imaging rates of 10^4 images per second (VLA D configuration) and has produced several tens of billions of images to date. Fast imaging has been demonstrated at the VLA, ATA, GMRT and KAT-7 radio interferometers.

Fast imaging has localized rotating radio transients[2] and pulsars, and is now being used to search for FRBs[3]. I will present the latest results from recent and ongoing VLA observing campaigns.

My talk will conclude with our plans to develop a real-time, commensal, fast transient search system at the VLA. Real-time transient detection not only provides fast response to events, it also makes it possible to trigger data recording for those brief moments when a candidate transient appears. Triggered data recording allows us to reduce the data flow dramatically, open access to even higher data rate observing, and make *commensal* observing possible. In this way, we will use this system to turn every VLA observation into a portion of a massive transient survey.

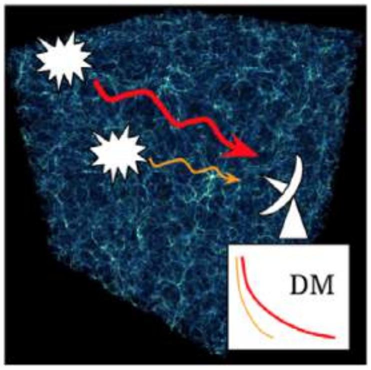


Figure 1: FRB dispersion measure may be a proxy for distance and a novel probe of the IGM. Localizing and associating FRBs with sources of known distance (e.g. a host galaxy) is key to understanding their origin and using them as probes.

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[1] See `https://github.com/caseyjlaw/rtpipe`.

[2] C. J. Law, G. C. Bower, M. Pokorny, M. P. Rupen, and K. Sowinski. The RRAT Trap: Interferometric Localization of Radio Pulses from J0628+0909. *ApJ*, 760:124, dec 2012

[3] C. J. Law, G. C. Bower, S. Burke-Spolaor, B. Butler, E. Lawrence, T. J. W. Lazio, C. A. Mattmann, M. Rupen, A. Siemion, and S. VanderWiel. A Millisecond Interferometric Search for Fast Radio Bursts with the Very Large Array. *ApJ*, 807:16, jul 2015

Notes

CHIME as an FRB Machine

Boutiques & Experiments 2016: Radio – Thursday, July 21st, 2:15pm

Keith Vanderlinde (Dunlap Institute @ Toronto) for the CHIME-FRB Team

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a new, massively redundant close-packed transit radio interferometer. It is composed of 1024 dual-polarization feeds covering a 400-800MHz band, spaced along the focal lines of four adjacent 100m x 20m cylindrical reflectors. The design and primary goal of CHIME are cosmological, to study Dark Energy via measurements of the Baryon Acoustic Oscillation feature in 21cm emission from neutral hydrogen between redshifts 0.8 - 2.5.

Shortly after initial work began on CHIME, its near-ideality for transients and variables was noticed. Combining:

- wide field of view (~250 deg^2, stretching horizon-to-horizon N-S and roughly 2 degrees wide E-W)
- large collecting area (8,000 m^2)
- broad bandwidth (400-800 MHz)
- flexible software backend (allowing multiple simultaneous operating modes)

in a dedicated instrument that operates 24/7, CHIME has unprecedented sensitivity to variability on all timescales <10 min and >1 day. For example, by generating a handful tied-array beams, a custom pulsar backend can monitor every known pulsar in the northern hemisphere on a near-daily basis.

With the growing interest and rapidly evolving landscape of Fast Radio Bursts, an additional backend is being constructed to allow 24/7 searching in CHIME's entire field of view. The instrument uses FFT-beamforming to generate 1024 intensity beams at high (24kHz) spectral resolution and high (1ms) cadence, which are delivered to a dedicated processing engine for searching.

This engine is dominated by a CPU cluster which performs a highly efficient dedispersion transform and peak search, exploring DMs up to 10,000 pc/cm^3 and across a wide variety of parameters such as spectral index, scattering time, and intrinsic width. Candidate detections are sifted to remove RFI, known sources such as pulsars and RRATs, then grouped and assessed for quality. The highest quality events will be announced to the community in real time.

We are exploring additional techniques to increase science yield. A preliminary coherent de-dispersion will center sensitivity near some target DM, allowing us to maximize detection efficiency to a target population. The 16TB of correlator RAM allows full-array baseband data to be buffered for up to a minute, allowing polarization sensitive full interferometric reprocessing of interesting events.

CHIME-FRB will come online in 2017 and holds the potential to rapidly deliver a large population of fast transients.

Figure 1: The CHIME telescope, currently nearing completion. Commissioning will begin in late 2016, and a dedicated FRB backend will be deployed beginning in early 2017. The multi-year CHIME-FRB survey will begin later that year.

Notes

Deep synoptic array prototype for FRB localization

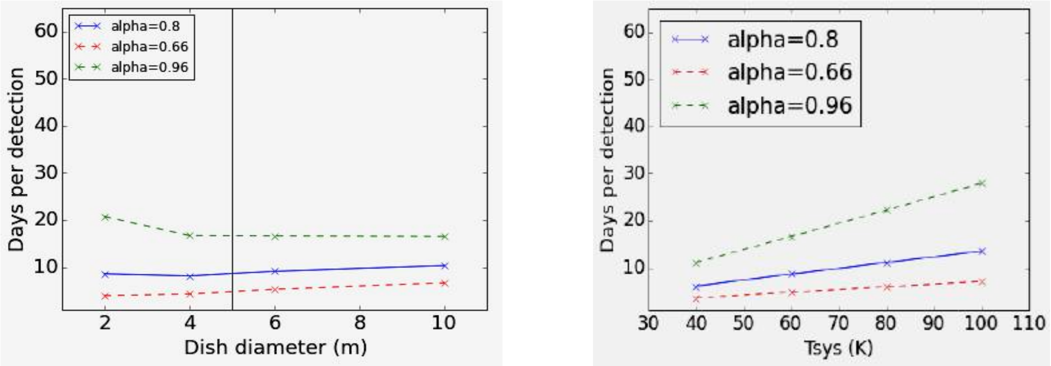
Vikram Ravi – Caltech, for the DSA team

The previous abstracts in this booklet have focussed on using large pre-existing, multi-purpose decimetric radio telescopes – UTMOST, JVLA, CHIME – for fast radio burst (FRB) science. Here I describe a complementary approach to the problem of understanding the origins of FRBs: the construction of a small, dedicated instrument with a clear (obdurate) focus on the specific problem of *directly localizing FRBs to individual astronomical objects*.

Of the five large telescopes to have reported substantial FRB searches, the two least-sensitive instruments (Parkes, UTMOST) have detected the most events. This remains surprising even after accounting for survey selection functions, because it is unexpected for a source population that is extragalactic but not remarkably distant. If FRB sources are uniformly distributed in Euclidean space, the number of events with fluence >F is expected to scale as F^(-α) with α = 1.5 for any luminosity function. However, by comparing the FRB detection rates at Parkes, the JVLA, Arecibo, and the substantially less sensitive Allen Telescope Array (ATA), we found $0.7 < \alpha < 1.1$ (90% confidence; Vedantham et al. 2016). Perhaps more robustly, similar values of α were suggested by the rate of multiple-beam FRB detections with the 13-beam receiver at Parkes; >2 FRBs are seen in multiple beams although the beam-responses only overlap at the nulls. Together, we find $0.66 < \alpha < 0.96$. Values of $\alpha < 1$ imply that, all else being equal, smaller dishes (with larger fields of view) will detect FRBs more often than larger dishes (!), presumably up to some maximum fluence cutoff for FRBs.

It was with this background that the Deep Synoptic Array (DSA) prototype was conceived. The DSA is a planned `large-N small-D' instrument (PI Gregg Hallinan) with unmatched survey speed between 1 – 2 GHz, aimed at radio transients on all timescales and deep all-sky continuum and spectral imaging. The DSA prototype, jointly funded by Caltech (PI Shri Kulkarni) and JPL (PI Jonathon Kocz), is the first instrument designed with the singular science goal of meaningfully localizing FRBs. Our design philosophy was to create the simplest, most cost-effective system that is capable of localizing FRBs comparable to the brightest events detected at Parkes.

The DSA prototype (January 2017 deployment) will consist of 10 5-meter dishes, equipped with single-pixel, dual-pol receivers capable of 60 K system temperature between 1280–1530 MHz (verified on-sky), sited at Caltech's Owens Valley Radio Observatory. A combined FPGA (5x CASPER SNAP-1) and GPU (6x NVIDIA GTX1080) digital backend will process 250 MHz of bandwidth per polarization, detecting FRBs in real time in the incoherent sum of 2048-point spectra from all antennas. Localizations of <3'' will be achieved by post-processing buffered raw voltage data. We expect an FRB detection rate that is >75% that of Parkes, or one event every 10-20 days; a detailed prediction is below.



Predicted number of days per FRB detection with the 10-element DSA prototype, for different dish diameters (left) and system temperatures (right), and values of the logN-logS slope α. We assume a 10 sigma detection threshold, 225 MHz of bandwidth, and an FRB rate of 1.2×10^4 /sky/day > 1.8 Jy ms. On the left, we assume a 60 K system temperature, and on the right we assume 5 m dishes.

H. K. Vedantham, V. Ravi, R. M. Shannon, G. Hallinan, The Fluence and Distance Distributions of Fast Radio Bursts, ApJ accepted, arXiv:1606.06795 (2016)

Notes

Transients with Apertif
Joeri van Leeuwen

Apertif is a highly innovative receiver system that was installed at the Westerbork Synthesis Radio Telescope this spring. Its factor 30 increase in field-of-view allows astronomers to survey the entire sky at 1.4 GHz with an unprecedented combination of sensitivity and speed (Oosterloo et al. 2010). Through ARTS, the Apertif Radio Transient System (van Leeuwen 2014), we will carry out simultaneous imaging and time-domain studies of the full 9 $\deg^2$ field of view.

Over a period of 4 years starting early 2017, we will carry out an all Northern Sky survey of 15,000 $\deg^2$ at 3-hr pointings (6 hrs in the Galactic Plane), a large-area survey covering 3,500 $\deg^2$ with 12-hr pointings, and a medium-deep survey over $\sim$450 $\deg^2$, using seven 12-hr repeats (Apertif Survey Team 2016).

In these multiple passes we search for *slow* image-plane transients. The 7 repeat visits of the medium deep fields, especially, provide a cadence of months to years with emphasis on the 3-month peak timescale at 1.4 GHz for the afterglows for Gamma Ray Bursts and Tidal Disruption Events. Apertif is uniquely sensitive to transients at that timescale and rate.

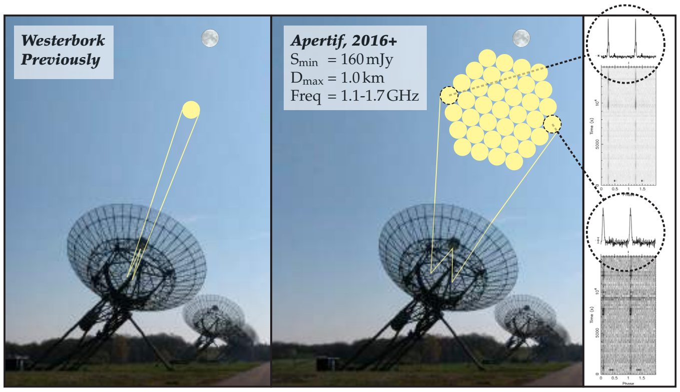


Figure 1: Westerbork previously (left) and now (right). Fully right, prompt emission from pulsars B0329+54 and B0355+54 as simultaneously detected at the edges of the 9 $\deg^2$ field.

But the largest impact will be from the 24/7 time-domain survey for *fast* transients. Such millisecond transients appear all over the radio sky. These point to extreme energies, magnetic field strengths, gravitational fields, and densities. The physical conditions on display in these sources must far exceed any terrestrial laboratory. Some of these short-lived radio bursts can be traced to one-off flashes from pulsars, but the Fast Radio Bursts (Lorimer et al. 2007; Spitler et al. 2016) clearly originate far outside our Galaxy, and continue to defy explanation. The first aim of the Apertif pulsar and transient survey is to enable progress in understanding the astrophysics that powers these brief, extremely energetic extragalactic event. This survey, ALERT (van Leeuwen 2016), increases by a factor of 10 our exploration volume for such fast transients throughout the Universe. Over is lifetime ALERT can detect tens of extragalactic bursts in real-time, and trigger follow-up ranging from e.g. LOFAR, for exceedingly accurate localization; up to optical and x-ray observatories. The second aim of this Apertif pulsar and transient survey is to characterize, to much lower luminosity than before, the population of intermittently active neutron stars, and better understand the Galactic neutron-star population.

The entire Apertif chain is funded, from front-end instrumentation, through back ends, to survey science teams. A demonstrator hardware system has already detected two far-apart pulsars (Figure 1), while the demonstrator pipelines pick up FRBs in Parkes data. Commissioning of the final system started July 1. From 2017 we expect this wide-field radio telescope to find many transients, both fast and slow, in real time.

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APERTIF APERture Tile In Focus
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erc European Research Council Established by the European Commission
NWO
ASTRON
netherlands eScience center
NOVA

Notes

A Search for Fast Radio Bursts with the GBNCC Survey

Pragya Chawla, McGill University
on behalf of the GBNCC collaboration

Fast Radio Bursts (FRBs) are millisecond-duration bursts with dispersion measures (DMs) greatly exceeding the maximum predicted along the line of sight due to our Galaxy. All known FRBs have been detected at frequencies greater than 700 MHz. Detection at lower frequencies is crucial for understanding properties of FRBs such as spectral index and pulse profile evolution with frequency. The upper limits on FRB rate reported thus far from low frequency radio surveys are not particularly constraining because of limitations in total observing time and comoving volume searched. With a total on-sky time of 79 days, the Green Bank Northern Celestial Cap (GBNCC) Pulsar Survey (Stovall et al. 2014) can provide the strongest constraints yet on FRB rate in the frequency range of 300-400 MHz.

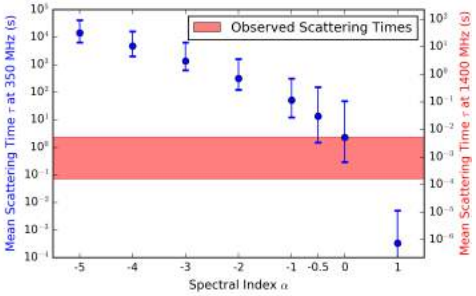


Figure 1: Mean scattering time at 350 MHz that could render FRBs undetectable with GBNCC for different spectral indices. The range of scattering timescales of all known FRBs at 1.4 GHz (Cordes et al. 2016) have also been plotted.

The GBNCC survey is being conducted at 350 MHz using the Green Bank Telescope. Each pointing is observed for 120 s and data spanning 100 MHz of bandwidth split into 4096 channels is recorded with a sampling time of 81.92 μs. Pointings amounting to a total on-sky time of 56 days were searched to a DM of 3000 pc cm^{-3} while the rest (29% of the total time) were searched to a DM of 500 pc cm^{-3}. We searched for FRBs using the PRESTO software package and a grouping and rating algorithm, RRATtrap (Karako-Argaman et al. 2015). We did not find any FRBs in the pointings observed until May 2016. Assuming Poisson statistics, we estimate a 95% confidence upper limit on the FRB rate to be 3.8 $\times$ 10^3 FRBs sky^{-1} day^{-1} above a peak flux density of 1.5 Jy. Our rate estimate is consistent with the estimate reported at 1.4 GHz for the Parkes surveys, 3.3 $\times$ 10^3 FRBs sky^{-1} day^{-1} (Crawford et al. 2016) only if FRBs have an intrinsic spectral index $\alpha > 0.75$. The above limit assumes a Euclidean flux distribution and is valid only in the absence of scattering and free-free absorption.

However, scattering is one possible reason for our non-detection. Scattering from our Galaxy is unlikely to play a major role as only 2% of the total pointings have predicted galactic scattering time > 10 ms at 350 MHz. Figure 1 shows the mean scattering due to the host galaxy that would render FRBs expected for a particular value of spectral index undetectable with GBNCC. Given the observed range of scattering times at 1.4 GHz, we constrain $\alpha > -1$ in the absence of free-free absorption.

Estimating a maximal redshift of 0.4 (see Chawla et al. in prep. for details) being probed by the survey, we find a spectral index α_{lim} for which the peak flux density at z = 0.4 is equal to the survey sensitivity. Any spectral index $< \alpha_{lim}$ can be rejected as it would predict sensitivity to a greater redshift and hence detection of FRBs with GBNCC. In the scenario of free-free absorption with a hot ionized magnetar ejecta, we obtain $\alpha_{lim} = 0.4$ and for a cold molecular cloud having ionization fronts, $\alpha_{lim} = -1.2$ under the assumption of no scattering.

The current upper limit with GBNCC can be used to estimate the number of bursts that can be detected with current and upcoming surveys. Figure 2 shows the bursts per hour expected from other FRB searches in the presence of scattering and for a range of spectral indices ($-1 < \alpha < 2$). CHIME may detect as many as 65 FRBs a day, making it well suited to obtain interesting constraints on spectral index, degree of free-free absorption and pulse profile evolution across its bandwidth (400-800 MHz).

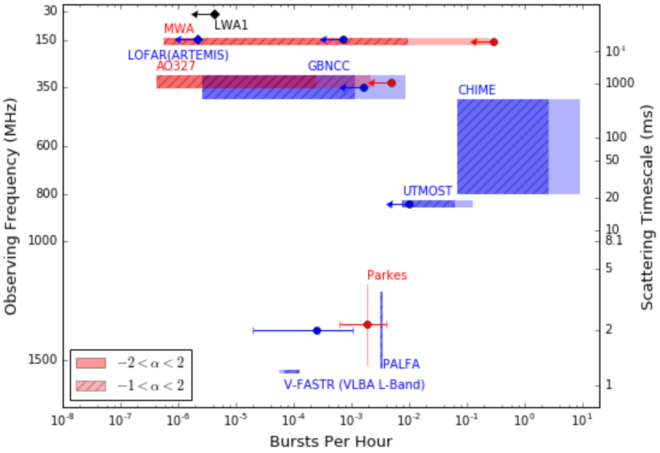


Figure 2: Bursts per hour expected to be detected by other FRB surveys based on existing 1.4-GHz rates and our constraint on the spectral index ($\alpha > -1$). The upper limits reported by different surveys have also been plotted.

FRB: PSR, SGR, ?

J. I. Katz

Fast Radio Bursts are brief (some widths $W \lesssim 1\,\mathrm{ms}$, other W, broadened by scattering, up to $\sim 10\,\mathrm{ms}$) and apparently at "cosmological" distances ($z \sim 1$). Therefore, they must radiate powers $\gtrsim 10^{38}$–10^{40} Γ^{-2} erg/s, where the bulk Lorentz factor Γ reflects possible beaming. This is 10–12 orders of magnitude less than the power of GRB, but appears as coherent radio emission with very high brightness temperature. At least one FRB repeats.

Occam's Razor is essential in science: without it we could not test hypotheses, because any non-conforming observation could be explained by an additional hypothesis. Hence we consider only hypotheses that can explain repeating FRB. Sometimes Occam is wrong (GRB/SGR were once conflated), but we cannot assume that without compelling evidence.

FRB must be compact ($r \lesssim Wc\Gamma^2 \sim 3 \times 10^7 \Gamma^2\,\mathrm{cm}$) and energetic. This points to NS or BH as sources. NS offer three sources of energy: gravitational, magnetic and rotational. BH, after their initial ring-down, only offer gravitational energy.

Gravitational energy can be released only by accretion, either by coalescence of two compact objects (as in some GRB models) or by accretion of a smaller object (proposed for SGR and FRB). Where accretion is known (X-ray binaries) it produces thermal X-rays, not coherent radio emission.

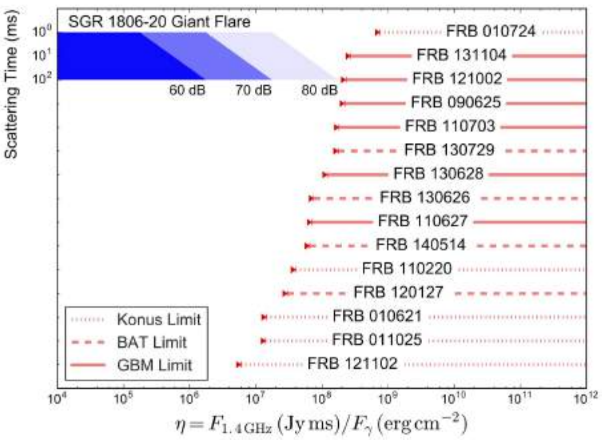
Rapid release of magnetostatic energy in "magnetars" (NS with $B \geq 10^{14}$ gauss, larger than those of radio PSR) is believed to power SGR of $\gtrsim 10^{47}$ ergs. The energy is released episodically, so that it may all be concentrated into brief bursts. However, in SGR it appears as X-rays or "soft" gamma rays ($\sim$ 10–300 keV), with only weak and long-lived radio afterglow. One Galactic SGR (SGR 1806-20) was fortuitously observable by a radio telescope during outburst, and no FRB was seen. The closer distance of this Galactic object would imply a signal $1^{11}\times$ that at cosmological distance, more than offsetting the 60 db side-lobe suppression. However, the FRB event rate is about 10^{-4} of the Galactic SGR giant flare rate; perhaps super-SGR, so far unobserved, produce FRB?

Giant PSR nanoshots have had brightness temperatures even greater than those of FRB, but their powers fall short by several orders of magnitude. The rotational energy of NS is released continually, as inferred from spindown, so production of FRB must be extremely inefficient (duty factor 10^{-8}). The field and rotation frequency are constrained $B_{15}^2 \Omega_4^4 W_{-3} > 1.6 \times E_{40}$ by the observed FRB power. The observation of repetitions over 3 y sets a lower bound on the spindown time, implying $B_{15}^2 \Omega_4^2 < 10^{-5}$. These constraints limit the PSR model to a small corner of parameter space. The energy requirements imply a spin period $< 5\,\mathrm{ms}$, a bound that is tighter if radiation is inefficient.

Magnetar Giant Flares and Galactic FRBs

Shriharsh P. Tendulkar (McGill University)

from the results of Tendulkar, Kaspi & Patel 2016, ApJ, *in press*, arXiv:1602.02188



Since the first announced Fast Radio Burst (FRB, Lorimer et al, 2007), extragalactic magnetar giant flares (GFs) have been the most popular and perhaps the most promising explanation for FRBs. The fast (~millisecond timescale) rise times of GFs, the extreme energy releases (~$10^{44\text{-}46}$ erg) and origin near dense interstellar medium clouds are good fits for the observed timescales, inferred cosmological distances and dispersion measures (DMs) of FRBs. For a thorough review of the observed and inferred properties of FRBs, please read Katz (2016). If this hypothesis is true, we expect that Galactic magnetar GFs would give rise to extraordinarily bright (~10-100 MJy) radio flares.

We analysed archival data from the Parkes radio telescope which was observing a location 35.6° away from SGR 1806-20 during its giant γ-ray flare of 2004 December 27. We showed that no FRB-like burst counterpart was detected, and set a radio limit of 110 MJy at 1.4 GHz, including the estimated 70 dB suppression of the signal due to its location in the far side lobe of Parkes and the predicted scattering from the interstellar medium. The upper limit for the magnetar giant flare radio to γ-ray fluence ratio is $\eta_{\mathrm{SGR}} < 10^7$ Jy ms erg^{-1} cm^2. Based on the non-detection of a short and prompt γ-ray counterpart of fifteen FRBs in γ-ray transient monitors, we set a lower limit on the fluence ratios of FRBs to be $\eta_{\mathrm{FRB}} > 10^{7\text{-}9}$ Jy ms erg^{-1} cm^2. The fluence ratio limit for SGR 1806-20 is inconsistent with all but one of the fifteen FRBs (Figure 1).

A straightforward way to reconcile the magnetar GF hypothesis (among others discussed in Tendulkar et al. 2016) is to propose that the observed fluence ratio, η_{obs}, can vary wildly between different magnetars and even different bursts of the same magnetar. This could either be due to the intrinsic variation of the emission mechanism or due to beaming of the radio pulse toward or away from the observer. In this scenario, extragalactic FRBs would be a radio-bright fraction of GF events. However, the volume rates of magnetar GFs are just comparable to (and not significantly higher than) the rates of *observed* FRBs up to a typical distance scale of 1-2 Gpc, leading to a rate mismatch with the much higher inferred rate of FRBs.

The rate mismatch may be alleviated if the more frequent intermediate flares (energies of $10^{38\text{-}40}$ erg) can produce bright radio bursts. Wide-field experiments such as DSA-10, in combination with X-ray monitoring missions, can help address this question by focussing on very active magnetars (such as SGR 1935+2154 in its current state).

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Katz, J. I. 2016, *Mod. Phys. Lett. A*, 31, 14, 1630013

Monitoring Pulsars and the ISM with CHIME

Shriharsh P. Tendulkar (McGill University) on behalf of the CHIME Collaboration

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a telescope being constructed for mapping the Universe at redshifted 21-cm wavelengths. Its large collecting area (80m x 100m), field of view (250 deg^2) and bandwidth (400-800 MHz) also make CHIME an excellent tool for finding Fast Radio Bursts (FRBs, see abstracts by K. Vanderlinde & A. Josephy) and, as we discuss here, for the dedicated study of pulsars and the interstellar medium (ISM). The CHIME pulsar backend (CHIME-P) will observe every known, visible (declination > -20°) millisecond pulsar daily and the all the slower pulsars every 11 days with a collecting area similar to the 100-m Green Bank Telescope.

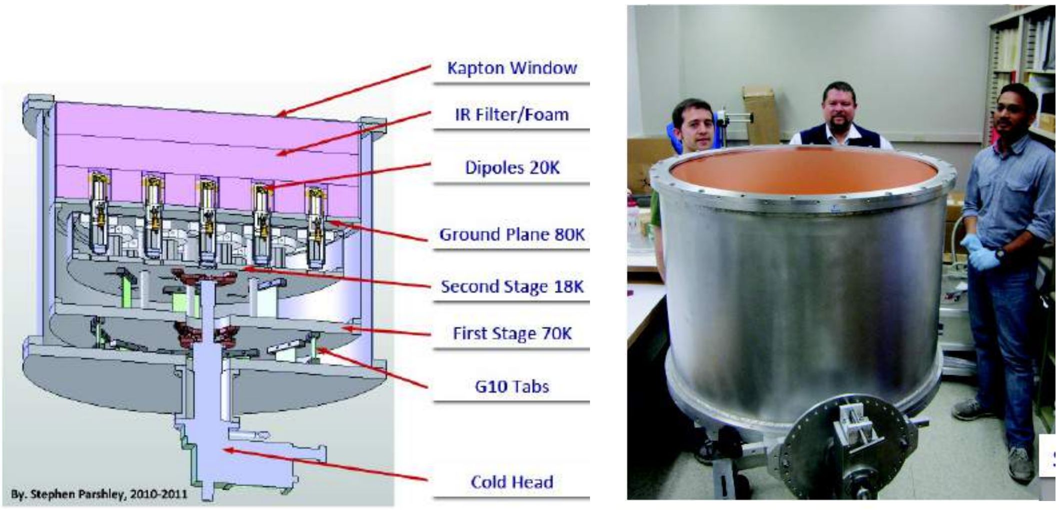
CHIME-P Science Goals:

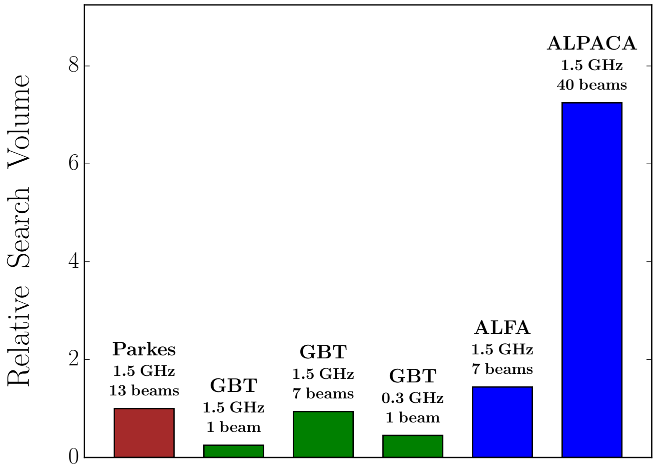
1) *NANOGrav/IPTA*: CHIME-P will monitor ToAs, dispersion measure (DM) variations and profile changes for each of the 38 NANOGrav pulsars daily. Combined with independent higher frequency ToA measurements from Arecibo Observatory and the Green Bank Telescope, we estimate an improvement in the timing precision by 50% for half of the visible NANOGrav pulsars and by at least 25% for the rest.
2) *Pulsar Binaries*: CHIME-P will perform long term monitoring of pulsars in binaries for testing GR in strong gravity, companion ablation via eclipse monitoring, and study binary evolution via transitions of low mass X-ray binaries between accretion powered and rotation powered states.
3) *Pulsar Emission Mechanisms*: We have little understanding about the physical radio emission mechanism that exhibits diverse observed phenomenology --- pulse nulling, magnetospheric switching, mode changes, giant pulses, as well as radio magnetar outbursts. CHIME-P will provide a well-sampled dataset of pulse profile variations, pulse duty cycles for pulsars of all ilks.
4) *Pulsar glitches and timing noise*: The same dataset will also allow a detailed study of pulsar glitches (sudden spin-ups), glitch recovery and timing noise for rarely glitching millisecond pulsars to frequently glitching young pulsars, constraining their physical structure.
5) *ISM propagation effects*: CHIME-P will create an unprecedented data set of full Stokes polarization measurements over a very wide frequency band obtained daily in the direction of all known pulsars. This dataset will allow us to better understand the variations in the ISM via DM, scattering timescale, scintillations, extreme scattering events (ESE) and rotation measure (RM) observations.

CHIME-P will complement FRB searches by providing insight into high luminosity pulsar/magnetar emissions (as prime FRB generation candidates) and the scattering and scintillation effects of the ISM on FRB propagation.

CHIME Pulsar Backend Cluster:

The CHIME correlator forms 10 tied-array beams that track targets for a duration of ~10-15 min as they cross the meridian. Each beam is a dual-polarization voltage series with 1024 x 390 kHz frequency channels with a data rate of 6.4 Gb/s per beam. The pulsar backend consists of 10 computing nodes (+1 spare) each with an NVIDIA Titan X GPU for coherent dedispersion and full Stokes polarimetry. This setup will allow for pulsars to be recorded in search mode (recording few μs sampled intensity time series data to disk) or in fold mode (recording intensity data folded at pulsar ephemeris to disk). The data from the 10 nodes (~ 700 GB/day) will be stored on-site in 144 TB archiving machine and periodically shipped to long term storage site. Pulsar timing data will be regularly processed onsite to create time of arrival (ToA) measurements for the NANOGrav database.





Top: (left) AO-19 cooled phased array feed (BYU, Cornell, NRAO). (right) Picture of the cryostat. This L-band system achieved T_{sys} *of 35 K on a 20-m telescope. From a presentation made by A. Roshi (NRAO). Bottom: The "grasp" of AO-40 (a proposed 40-dipole cooled phased array for the Arecibo telescope) relative to that of other phased array feeds. More details can be found in G. Cortes-Medellin et al. (2016), Concept Design of an 80 dual-polarization-element Cryogenic Phased Array Camera for the Arecibo Radio Telescope. SPIE International Symposium on Astronomical Instrumentation. Vol. Ground-based and Airborne Instrumentation for Astronomy VI.*

Session B: Propagation

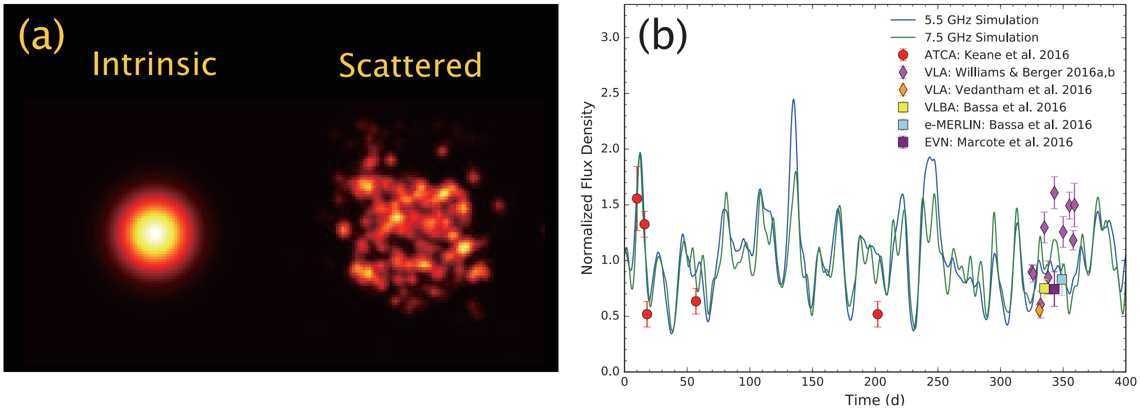
Talks

B1. Galactic Diffractive Scintillations & Extragalactic Scattering of FRBs (Jim Cordes)

B2. Interstellar Scintillation and Radio Counterparts of FRBs (Kazunori Akiyama)

B3. Extreme Scattering Events (Keith Bannister)

B4. Probing the intergalactic medium (Takuya Akahori)



Simulated images showing the effects of refractive interstellar scintillation on a Gaussian source more compact than the refractive scale. Refractive scintillation blurs source intrinsic images and generates refractive substructures (a). The resultant light curves will show rapid, synchronized variations at radio frequencies with a moderate spectral modulation (b). This, for instance, can explain current observed light curves of the radio counterpart candidate of FRB150418 (data points in the panel (b)), which may invalidate its association with FRB150418 (the panel (b); Akiyama & Johnson 2016). This clearly demonstrates that refractive interstellar scintillation is a critical consideration for searches of associated afterglows of the FRBs and other compact transients at radio wavelengths. Figure supplied by K. Akiyama.

Galactic Diffractive Scintillations and Extragalactic Scattering of Fast Radio Bursts

J. M. Cordes, Cornell University, July 11, 2016

Fast radio bursts with $\sim$ms durations are intrinsically compact enough to show intensity scintillations from scattering in the Milky Way's turbulent, ionized interstellar medium. However, the angular scattering of FRBs from extragalactic plasma can alter the presence and properties of Galactic scintillations. A full understanding of FRB selection effects and source locations therefore requires consideration of scattering along the entire line of sight to each FRB.

I will summarize the optics of interstellar diffraction and define key quantities needed for a discussion of FRBs. Most of what we know about diffractive interstellar scintillation (DISS) is based on pulsar measurements combined with angular scattering of AGNs and other sources. They demonstrate that scattering is from a medium with a wide range of scales from $\sim 10^3$ km to $\gtrsim$ pc consistent with a Kolmogorov-like spectrum, perhaps augmented by other structures.

Basic points about DISS relevant to an FRB discussion are:

- DISS is 100% modulated for a point source measured in a narrow bandwidth.
- Intensities vary with both time ($\sim$ min to hr) and frequency ($\sim$ kHz to 100s of MHz).
- Characteristic DISS times and bandwidths are strong functions of frequency and become rapidly smaller at lower frequencies and for longer path lengths at low latitudes.
- Fully modulated DISS occurs below a transition frequency ~ 5 GHz at high Galactic latitudes and ~ 100 GHz toward the Galactic center.
- The geometry of source, scattering medium, and observer strongly affects DISS properties.
- DISS can be quenched by averaging over a wide receiver bandwidth and by extragalactic scattering that angularly broadens a source; these effects are severe at low frequencies.

DISS has likely had a strong influence on detection of the known population of FRBs:

- A two-medium model, at minimum, is required to understand FRB yields in surveys and followup observations.
- A picture where all FRB sources repeat with a possibly large rate, cannot be ruled out at present.
- The role of DISS depends on the size of the source population:
    1. Extreme-value scintillation boosts larger than x10 can be expected from a large population, providing both the low yield in a large survey and the lack of redetections in reobservations with many fewer statistical trials.
    2. A small source population provides fewer statistical trials of the scintillation boosts. In that case, intermittency of FRBs is more likely intrinsic to sources.
- DISS gives the largest boosts at high Galactic latitudes but essentially none at low latitudes; in the latter case refractive scintillations (RISS) are relevant.
- The lone repeating FRB has quenched DISS so its detection is due to Arecibo's sensitivity and RISS.
- Strong extragalactic scattering may be accompanied by significant free-free absorption at frequencies below ~ 1 GHz. Other selection effects will also operate at low frequencies.

I will also discuss (1) constraints on the location of extragalactic scattering (most likely in host galaxies); (2) a new method for detecting FRBs in radio astronomy data; and (3) a code package (`MWscint.py`) based on NE2001 that provides probability distributions for the combined modulations from DISS + RISS for input radio frequency, bandwidth, direction (Galactic coordinates), and source size. I will briefly mention the possible role of extreme scattering eventss (ESEs) and gravitational microlensing on FRB detections.

Notes

Interstellar Scintillation and Radio Counterparts of FRBs

Kazunori Akiyama (MIT Haystack Observatory) & Michael D. Johnson (CfA)

Fast radio bursts (FRBs) are one of the most intriguing source classes, not only for the astrophysical processes causing one of the most energetic but shortest bursts in the universe but also for their astronomical aspect as a unique probe of the intergalactic medium. The population of nearly 20 FRBs detected so far is highly inhomogeneous and diverse, and their observational properties are challenging to explain with a single type of progenitors. Searches for counterparts of FRBs – for instance, associated afterglows – are of significant importance to localize the FRBs and are crucial to understand their origin.

Refractive interstellar scintillation is a critical consideration for searches of associated afterglows at radio wavelengths. The tenuous ionized interstellar medium along the line of sight can introduce rapid variability of compact radio sources such as active galactic nuclei (AGNs) on timescales comparable to potential afterglows of the FRBs. Thus, it is essential to distinguish between associated afterglows and rapidly variable scintillating sources close to FRBs. This issue is particularly important for FRBs at lower Galactic latitudes where scattering is significantly stronger than at higher Galactic latitudes.

We have recently demonstrated the fundamental importance of refractive scintillation for identification of radio counterparts in a theoretical study on the effect of scintillation of the FRB 150418 (Akiyama & Johnson 2016, [1]), which Keane et al. (2016) have recently discovered with a promising radio counterpart at 5.5 and 7.5 GHz – a rapidly decaying source on timescales of $\sim$6 days. The analytical theory of refractive scattering and our numerical simulations show that the reported observations of the claimed radio counterpart (e.g., Keane et al. 2016; Williams & Berger 2016; Vedantham et al. 2016) are consistent with scintillating radio emission from the core of a radio-loud AGN having a brightness temperature of $T_\mathrm{b} \gtrsim 10^9$ K, compatible with faint AGNs.

In future surveys of the FRBs, what kind of observations are useful for evaluating effects of refractive scintillation and identification of associated sources? First, it would be essential to test for the presence of modulations in spectra and light curves due to refractive scattering. Follow-up multi-frequency observations will be useful if they have an interval comparable to or shorter than the refractive time scale, and a duration longer than it. Secondly, the source compactness of counterpart candidates will be important, since refractive scintillation can only cause flux variability if the majority of the source flux originates in the compact core emission. Therefore, size measurements with VLBI would be of great importance to conclusively confirm the role of the refractive scintillation on the candidates. Third, as demonstrated in Akiyama & Johnson 2016 [1], development of tools to simulate scintillating light curves will be important to evaluate the refractive scintillation theoretically for comparison. We have used an open-source python package for simulating scattered images and light curves (ScatterBrane; [2]). It can numerically simulate both diffractive and refractive scintillation for given scattering and source parameters. The scattering parameters can be estimated a priori using publicly-available Galactic free-electron models (e.g., NE2001; Cordes & Lazio 2002, 2003). Both intensive observations and numerical simulations with such tools are essential to conclusively determine the importance of scintillation for the candidate afterglows of FRBs and other compact transients.

References:

1. Akiyama & Johnson 2016, ApJL, 824L, 3A

2. ScatterBrane: a python package for simulating realistically scattered images and light curves; `https://github.com/krosenfeld/scatterbrane`

Notes

Extreme Scattering Events

Keith Bannister
Australia Telescope National Facility

A long-standing puzzle in the interstellar medium

Extreme Scattering Events (ESE, Fiedler et al., 1987) are distinctive fluctuations in the light curve of a radio source (Fig. 1), typically an Active Galactic Nucleus (AGN) or pulsar. They are caused by high column-density plasma in the Milky Way acting like a lens, magnifying and demagnifying the source as it transits in front of it. ESEs are probably better named Plasma Lensing Events, but I will continue with ESEs to be consistent with the literature.

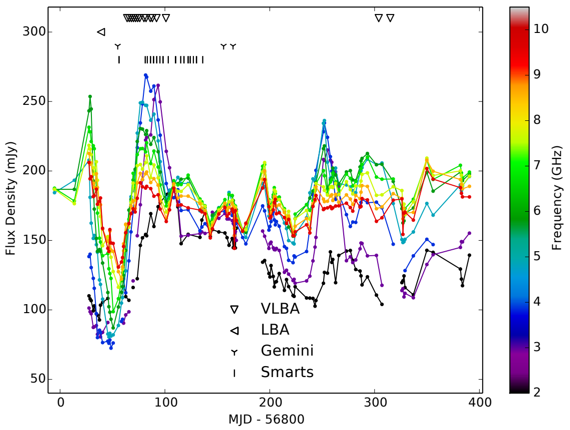


Figure 1: Left: Multi-frequency ATCA light curves for a recent ESE. From Bannister et al. (2016).

ESEs are important because they challenge our understanding of the interstellar medium. The lenses appear to be discrete structures, as distinct from turbulence, because they often occur on otherwise quiet lines of sight. The lenses must be Galactic, have sizes ∼AU to explain the event time-scales, and have angular sizes $\gtrsim$ source sizes ($\gtrsim 0.1\,\mathrm{mas}$) in order to create significant magnifications. The high event rate (1 per 2000 sources at any time) and small size of the lenses, implies volume densities $10^3 - 10^6\,\mathrm{pc}^{-3}$ depending on the assumed geometry. Studies of in-progress ESEs with VLBI, HI absorption, and rotation measures failed to make any conclusive findings (Clegg et al., 1996; Lazio et al., 2000, 2001; Pushkarev et al., 2013). This suggests that ESEs are they are a pervasive and poorly understood component of the ISM.

One key problem is understanding the shape of the lens. If one assumes the lens is a spherical cloud, then the pressure required to create the observed refraction angles ($\sim 1\,\mathrm{mas}$) is some $\sim 10^3$ times larger than the diffuse ISM. Such clouds, even they could form, could not survive long enough to be detected in such large numbers. Attempts to evade this problem by invoking sheets seen edge-on (e.g. Pen & King, 2012; Goldreich & Sridhar, 2006), yield light curves which are at odds with the Fiedler data (Walker, 2007), and also have been falsified in one case (Bannister et al., 2016). A model of a cold self-gravitating clouds by Walker & Wardle (1998) solves the pressure problem by invoking gravity as the confining force, but this in turn implies that the such clouds must make up a substantial fraction of the mass of the Galaxy.

A new detection method: the spectral signature of plasma lensing

When a plasma lensing event is in progress, the radio spectrum of the background source changes from a featureless continuum to one which is highly structured. This is a result of the λ^2 dependence of the plasma refractive index, which puts the lens focus closer to the observer at some frequencies than others. Our survey on the Australia Telescope Compact Array surveys $\sim 10^3$ compact AGN per month, looking for highly variable and highly structure spectra. So far we have discovered 11 candidate plasma lensing events—3 of which clearly match the archetypal pattern of an ESE, the remainder of which do not—since our observing program began in 2014 April – more than what Fiedler et al. (1987) found in seven years! Moreover, we recognise these events in real-time and gather detailed multi-wavelength information on each one while the event is *in progress*.

As an ASKAPs representative at B&E 2016: ASKAP will begin early science observing by the end of 2016 with 300 MHz of bandwidth, 12 antennas, 30 deg^2 instantaneous field-of-view, and an SEFD of 2100 Jy. We will be searching for radio counterparts of LIGO events ($30\,\mathrm{deg}^2\ \mathrm{hr}^{-1}$ at 0.11 mJy RMS), FRBs (37 Jy.ms 10σ over 360 deg^2) and other transients and variables such as ESEs ($210\,\mathrm{deg}^2 \times 7$ epochs at 40 μJy RMS per epoch). Ask me if you want to know more!

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Notes

Probing the Intergalactic Medium

"Boutiques & Experiments 2016: Radio", Pasadena, CA, July 21-23, 2016

Takuya Akahori, Kagoshima University, Japan

***Abstract* — Traditionally, the mean magnetic-field strength along a sightline is estimated as**

$$\langle B_{\|}\rangle \sim 1.232\ (RM/DM)\ \ [\mu G], \tag{1}$$

where DM is the dispersion measure in pc/cm^3 and RM is the Faraday rotation measure in rad/m^2. However, this method needs to be revised in the cosmological context such as extragalactic linearly polarized Fast Radio Bursts (FRBs) [1]. We suggest the use of the following formula,

$$\langle B_{\|}\rangle \sim 1.232\ (\langle 1+z\rangle/f_{DM})\ (RM/DM)\ \ [\mu G]. \tag{2}$$

For FRBs with DM < 1000 pc/cm^3, <1+z> ~ 1.0-1.5 and f_{DM} ~ 0.5 for the intergalactic medium (IGM) with temperature 10^5 - 10^7 K (or the warm-hot IGM, WHIM), according to the cosmological simulations with the standard cosmology.

Introduction — It has been predicted that WHIM dominates filaments of galaxies. The WHIM is, however, not well-proven by observations yet. If FRBs are extragalactic messenger then they inform us of the column electron density of the IGM via their DM. Moreover, an extragalactic linearly polarized FRB informs the column electron density weighted by the sightline component of the intergalactic magnetic field (IGMF) as RM [2].

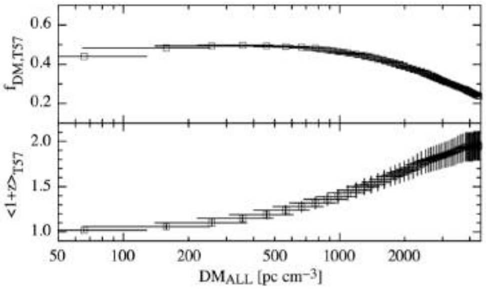
Motivation — The IGMF strength is estimated by the following steps; (i) extraction of the IGM's DM and RM from observed ones (which contain contributions of FRB's host galaxies, the Milky Way, etc), and (ii) estimation of the IGMF strength by the extracted DM and RM. This work focuses on the step (ii) and examine how the traditional estimate (Eq.1) compares with the IGMF strength in the WHIM, and propose a modified formula (Eq. 2). For this purpose, we only consider the contribution of the IGM to the DMs and RMs of FRBs.

Method — For an extragalactic source at $z=z_i$, DM and RM can be written at the observer's frame as

$$DM = C_{\rm D} \int_0^{z_i} \frac{n_{\rm e}(z)}{(1+z)} \frac{dl(z)}{dz} dz \quad {\rm pc\ cm^{-3}}, \tag{3}$$

$$RM = C_{\rm R} \int_{z_i}^{0} \frac{n_{\rm e}(z) B_{\|}(z)}{(1+z)^2} \frac{dl(z)}{dz} dz \quad {\rm rad\ m^{-2}}, \tag{4}$$

(see [1] references therein), where $n_e(z)$ is the proper electron density in the cosmic web at a redshift z in units of cm^{-3}, $B_{\|}(z)$ the sightline component of the IGMF at z in μG, and $dl(z)$ the sightline line element at z in kpc, with the numerical constants C_D~1000 and C_R~811.9. We study IGM's DM and RM based on cosmological simulations with the standard cosmology.



(Fig.1) The DM fraction (top) and the density-weighted redshift along sightlines (bottom) for the WHIM (T57), as a function of DM for all IGM along the sightlines (ALL), based on the data of cosmological simulations. Squares and error bars mark averages and standard deviations, respectively, for a large number of simulated FRBs.

Result I: DM Fraction — The DM through the cosmic web is dominated by the contributions from the WHIM and the gas in voids. Therefore, we need to consider the fraction of DM due to the WHIM, f_{DM}, so as to derive $\langle B_{\|}\rangle$ for the WHIM. The top panel of Fig.1 presents f_{DM} for the WHIM. Meanwhile, the RM through the cosmic web is induced mostly by the gas in galaxy clusters, and only a fraction of it is produced by the WHIM. If one refers X-ray data and excludes FRBs whose sightlines pass through galaxy clusters, the RM through the cosmic web is dominated by the contribution from the WHIM [1].

Result II: Redshift Dependence — Eqs. (3) and (4) indicate that DM and RM have different redshift dependence, which should be corrected in the estimation of $\langle B_{\|}\rangle$. Motivated by the difference, the correction factor, <1+z>, is defined as

$$\langle 1+z\rangle = \int_0^{z_i} \frac{n_{\rm e}(z)}{(1+z)} \frac{dl(z)}{dz} dz \Big/ \int_0^{z_i} \frac{n_{\rm e}(z)}{(1+z)^2} \frac{dl(z)}{dz} dz. \tag{5}$$

The bottom panel of Fig.1 shows <1+*z*> for the WHIM.

Result III: FRB's Redshift — Both f_{DM} and <1+*z*> can be evaluated for a given cosmology model solely from the DM of an FRB (Fig.1). FRB's redshift is thus not required to be known.

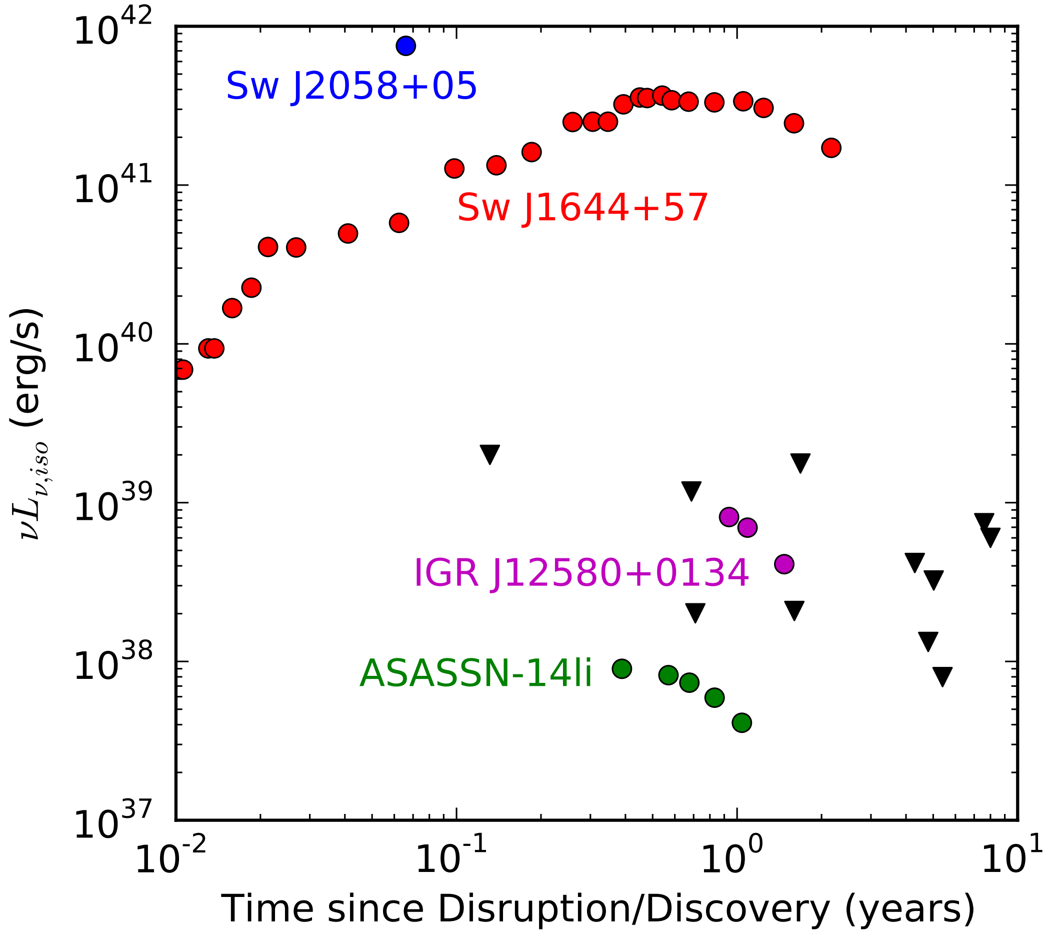
Conclusion — We have confirmed that Eq. (1) underestimates the sightline component of the IGMF in the WHIM by a factor of several, and Eq. (2) dramatically improves the estimate.

Acknowledgment & References — I thank Mareki Honma for travel support. This work is supported in part by JSPS KAKENHI Grant Number 15K17614 and 15H03639.

[1] T. Akahori, D. Ryu, & B. M. Gaensler 2016, ApJ, 824, 105

[2] Masui, K. Lin, H.-H., Sievers, J., et al. 2015, Nature, 528, 523

Notes



Radio observations of tidal disruption events (TDEs). The literature contains four TDEs with published radio detections: Swift J1644+57 (Zauderer et al. 2011; Berger et al. 2012; Zauderer et al. 2013), Swift J2058+05 (Cenko et al. 2012), IGR J12580+0134 (Irwin et al. 2015; Lei et al. 2016), and ASASSN-14li (Alexander et al. 2016; van Velzen et al. 2016). A selection of upper limits are also shown (van Velzen et al. 2013; Chornock et al. 2014; Arcavi et al. 2014). The two luminous Swift events are consistent with on-axis relativistic jets, while IGR J12580+0134 has been interpreted as an off-axis relativistic jet. The less-luminous ASASSN-14li is consistent with synchrotron emission from a non-relativistic outflow (Alexander et al. 2016). The upper limits imply that at most 10% of TDEs launch relativistic jets (van Velzen et al. 2013; Mimica et al. 2015), while the fraction of TDEs with non-relativistic outflows remains relatively unconstrained. Figure supplied by K. Alexander.

Session C: GW, High Energy and UV

Talks

C1. Spektr-RG Mission (Rashid Sunyaev)

C2. MAXI - Monitor of All-sky X-ray Image (Nobu Kawai)

C3. ULTRASAT (Eran Ofek)

C4. EM Observation of GW Sources (Linqing Wen)

Contributed abstracts

C5. Challenging science missions utilizing very small satellites (Yoichi Yatsu)

Spektr-RG Mission

Rashid Sunyaev, Max-Planck Institute for Astrophysics and Space Research Institute of Russian Academy of Sciences

In the last months of 2017 Russian State Corporation "ROSKOSMOS" is planning to launch SPEKTR-RG spacecraft onto L2 libration point of the Sun-Earth system. This spacecraft should carry aboard two X-Ray instruments: eRosita produced in Germany by Max-Planck Institute for Extraterrestrial Physics under the contract with DLR (German AirSpace Agency) and ART-XC, designed and produced by Space Research Institute in Moscow, VNIIEM (Sarov, Russia) and Marshall Space Flight Center (USA). Each of these instruments consists of 7 identical coaligned grazing incidence X-Ray telescopes with detectors sensitive in the spectral band 0.5 – 10 KeV (eRosita) and 6 – 30 KeV (ART-XC). The angular resolution of eRosita will reach 15" in the center of its field of view (close to one square degree) and 25" averaged over the field of view. Localization precision should be significantly better.

It is planned that Spektr-RG mission will spend 4 years scanning the sky to create the maps of the sky in these spectral bands. In the 0.5 – 2 KeV band these maps should be at least 20 times more sensitive than wellknown sky survey of the ROSAT spacecraft. This will be first sensitive all sky X-ray survey at the energies 2-20 KeV.

eRosita is able to discover and map up to 100 000 rich clusters of galaxies (practically all clusters with M > 2 10^14 Msun in observable Universe), more than 3 millions AGNs, at least 10 000 star forming galaxies and 10 000 massive elliptical galaxies, hundreds of thousands Galactic objects such as accreting white dwarfs and neutron stars, young and magnetically active stars, supernovae remnants, single neutron stars, radio pulsars etc, transient sources like tidally disrupted stars (by supermassive black holes), gamma ray burst afterglows etc. Whole sky is planned to be scanned 8 times during 4 years long sky survey. Each object will be observed 6 times during a day once per every sky scan. The minimal total exposure will be few kiloseconds per source. This will provide a unique information about variability of hundreds of thousands brightest sources on the whole sky. The total exposure per source will be significantly longer for two fields near North and Southern poles of ecliptic due to strategy of the scans, which will provide maps with two deep survey regions.

Huge samples of X-Ray selected AGNs and clusters of galaxies will open a possibility to use them for cosmology, for example to follow the growth rate of the large scale structure of the Universe up to redshifts 2 or 3 and to find baryonic acoustic oscillations in the spatial distribution of AGNs at different redshifts. The attempts to use the results of the sky survey for cosmology will request significant ground based support providing redshift information for hundreds of thousands newly discovered objects. The collaboration with ground based submillimeter telescopes creating SZ-effect maps will help to obtain a lot of information about properties of the rich clusters of galaxies.

ART-XC plans to produce first full sky hard X-Ray survey using grazing incidence X-Ray optics in the band from 6 to 20 KeV.
Planned lifetime of Spektr-RG spacecraft and its intruments is 7 years. After 4 years long all sky survey spacecraft will start to observe in detail most interesting objects discovered during sky survey.

Notes

MAXI – Monitor of All-sky X-ray Image

Nobu Kawai (Tokyo Tech) on behalf of the MAXI Team

Mission

Monitor of All-sky X-ray Image (MAXI) is an all-sky X-ray monitor onboard the International Space Station (ISS). It started observations in August 2009, and its operation is currently approved until March 2018. Further extension of the operation will be decided based on the review at the end of the current term.

Instruments and Operation

MAXI has two kinds of X-ray cameras, Gas Slit Cameras (GSC) with the field of view of $1.5^\circ \times 160^\circ$, and Solid-state Slit Cameras (SSC) with the field of view of $1.5^\circ \times 90^\circ$. The GSC is sensitive in the energy range 2–25 keV. While its instantaneous coverage is rather small (∼2% of the entire sky), ∼85 % of the entire sky is scanned every 92 minutes (*i.e.* orbital period of ISS). The GSC operation is suspended while passing the regions with high particle flux (at high latitudes and in SAA) resulting a duty cycle roughly 50%. The SSC covers lower energy band 0.7–10 keV, and has further reduced duty cycle, since it operates mostly during orbit nights. The ISS maintains real-time time communication for about 70% of the time during which the MAXI data are transmitted to JAXA within 10 seconds. Delivery of the data obtained out of ground contact may be delayed by up to 5000 seconds.

Nova Alerts

The GSC data are continuously examined by the ground transient detection pipeline ("Nova Alert System") on seven different timescales from 1 s up to 4 days. If the nova alert is triggered, the information on the transient X-ray source is delivered to the subscribers to a MAXI mailing lists of the appropriate source category, including that of "GRBs and unknown sources". If the trigger occurs at on a time scale of one orbit or shorter with sufficient statistics, the alert may be also sent directly as a GCN notice. The localization error of a constant source with a flux of ∼1 Crab (4–10 keV) is $\sim 0.2^\circ$ for a single scan. It reaches the systematic error limit of $\sim 0.1^\circ$ for 1-day integration (15 orbits). For a transient source like a short GRB that lasts for only a small fraction of the transit time, the location error is intrinsically large in the scan direction up to $\sim 3^\circ$, resulting in a long rectangular error box.

MAXI Transients (or lack of it)

MAXI has detected numerous outbursts from known and unknown X-ray sources. MAXI discovered 17 X-ray novae in seven years, that includes one white dwarf binary, six neutron star binaries, six black hole binaries (+candidates) and four unidentified sources. Despite of its rather small instantaneous field of view, MAXI/GSC has detected 82 GRBs (and candidates). Half of them have coincident detections with other satellites and confirmed as GRBs. The remaining half may contain various classes of sources including GRBs and short lived galactic transients, though there is no apparent sky distribution related to the Milky Way galaxy. Some of the MAXI-only event had timely followed up by Swift XRT with no detection. Possibly they are not GRBs, belonging to different classes of short transients.

MAXI can also contribute to search for X-ray counterparts of gravitational wave events. For GW150914 and GW151226, we covered most of the sky regions in the orbit following the GW detection with upper limits $\sim 1 \times 10^{-9}$ erg s^{-1} cm^{-2}.

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Notes

ULTRASAT

Eran Ofek

ULTRASAT is a proposed satellite mission to carry a UV sensitive space Schmidt telescope with an unprecedently large field of view, of over 235 deg^2 (PIs: Waxman & Kulkarni). *ULTRASAT* is a collaboration between the Weizmann Institute of Science, Caltech, JPL, the Israeli space agency, the Israeli aerospace industry and ElOp.

The main properties of *ULTRASAT* are as follows:

Field of view	235 deg^2
Band	220-280 Å(NUV)
Limiting mag	21.5 AB in 900 s
Aperture	33 cm
Focal length	32.8 cm
Orbit	Geo+300 km
Communication	continuous
SN shock cooling ($t < 1$ day)	$> 200\,\mathrm{yr}^{-1}$
SN	$> 1000\,\mathrm{yr}^{-1}$
SN shock breakout ($t < 30$ min)	$\sim 10\,\mathrm{yr}^{-1}$
GW triggers	$\approx 25\,\mathrm{yr}^{-1}$
AGN monitoring	$\sim 3 \times 10^4$
Stars monitoring	$\sim 10^5$

ULTRASAT will provide a factor of 300 improvement in the volumetric scanning speed[1] over past UV missions like *GALEX* (Martin et al. 2005), and even an order of magnitude higher volumetric speed than visible-light surveys like the Zwicky Transient Facility. The *ULTRASAT* mission is designed to discover and monitor large numbers of shock cooling, and shock breakout events from young supernovae. Furthermore, *ULTRASAT* will be capable of observing the entire error region of LIGO gravitational wave events within 20 min after alert. With the exception of ToO events, *ULTRASAT* will observe the same patch of sky for six month, with a time resolution of 300 s. After six months, *ULTRASAT* will switch to a new field of view in the opposite hemisphere.

Science goals

ULTRASAT will impact a wide range of fields, from stellar activity to low-surface brightness structures (30.5 AB mag arcsec^{-2}). Here we focus on two of its primary science goals - Supernovae (SN) and gravitational wave events.

Supernovae

Due to complications like mass-loss, turbulent convection and the hydrodynamic nature of the latest stages of stellar evolution (e.g., Woosley et al. 2002; Arnett & Meakin 2011a, 2011b; Langer 2012; Arnett, Meakin & Viallet 2014), the state and structure of supernova progenitors prior to their explosion is not well known. As this structure sets the initial conditions for the explosion, measuring it is of fundamental importance for SN physics, and as of yet not well understood explosion mechanism.

A promising method to study the nature of supernova progenitors is through their shock breakout and subsequent shock cooling (e.g., Colgate 1974; Falk 1978; Klein & Chevalier 1978; Matzner & McKee 1999; Nakar & Sari 2010; Rabinak & Waxman 2011). However, extracting the full potential of shock breakout and shock cooling requires UV observations and can not be fully achived using visible-light data (see Ganot et al. 2014 for details).

What are shock breakout and shock cooling? In a SN, at early times a photon dominated and mediated shock is propagating through the star envelope. The optical depth of the stellar envelope is high enough such that the photons are trapped within the propagating shock. When the shock reach the edge of the star the optical depth becomes lower and the photons can stream out. The duration of a shock breakout is the light crossing time of the star ($<$ 1 hr for a red supergiant) while its luminosity is proportional to the thermal energy stored in the envelope ($\propto R_*^2$). Following the shock breakout, on time scales of hours to a few days, we see emission from the inner parts of the stars (so called shock cooling). Both process contain information about the stellar radii, explosion energy per unit ejecta mass, and composition. All these are crucial for our understanding of the initial conditions of SN and the explosion mechanism.

Gravitational waves

Detection the electromagnetic signals from GW events is of paramount importance. This will enable us to study NS-NS merger physics, and constrain the ejecta mass. Furthermore, the localization of GW events have implications for more precise measurements of the merger parameters and even H_0.

Although there are huge uncertainties in the models for the electromagnetic (EM) signal from GW events, the best guess is that the afterglow will be blue at early times ($t < 1$ day) and will be faint and red at late times ($t > 1$ day). With its large instantaneous field of view, depth, prompt response, and the accessibility to $>$ 50% of the sky at any given moment, *ULTRASAT* is an excellent tool to look for the EM signal from GW events.

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[1] Refers to the volume the telescope scan to a given absolute magnitude in unit time.

Notes

EM Observation of GW Sources and a Potentially New Class of GW-EM Sources

We are entering the era of gravitational wave astronomy. With the first gravitational waves (GWs) discovered in 2015, many more GW sources are to be uncovered in the near future. In particular, breakthrough science from electromagnetic (EM) observations of gravitational wave sources is highly anticipated.

In this talk, I will discuss GW-EM observations of GW sources. My talk consists of two parts. (1) I will discuss the current capacity for prompt EM follow up observations of GW sources and type of sciences to be expected. I will discuss both the current and expected time scales to generate alerts from GW events, and the capacities of EM observatories that have signed MOUs for EM follow up observations. (2) I will propose a potentially new class of binary black hole mergers with EM counterparts.

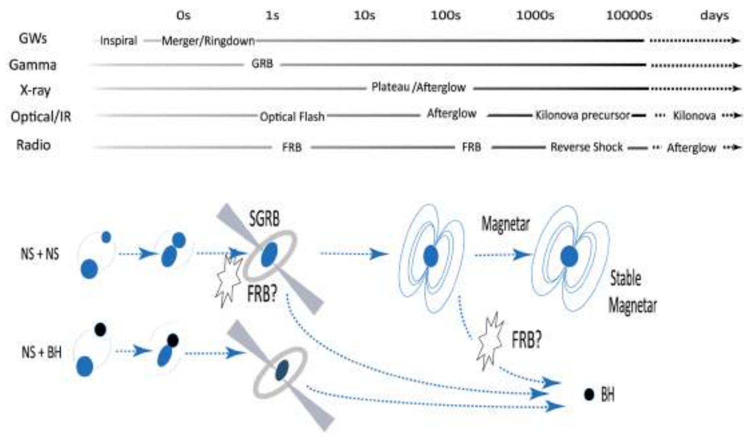

Figure 1: Schematics of proposed onset time, duration, and observable wavelength of possible EM outbursts following the mergers of BNS and NSBH systems (Figure taken from [1]).

The first part of the talk is based on our recent paper [1]. It has been long expected that compact binary mergers will be accompanied by EM outbursts, closely following the GW signal (Fig. 1). On the other hand, a large fraction of binary coalescence sources are expected to be detectable tens of seconds before the binary coalescence for advanced GW detectors at design sensitivity. An early warning from GW triggers is therefore in principle possible at tens of seconds before the binary merger. For binary neutron star mergers associated with short duration gamma-ray bursts (SGRBs), rapid EM follow-ups have the potential to capture the prompt emission, early engine activity, or reveal any potential by-products such as magnetars or fast radio bursts. One of the main challenges is that the nominal angular resolution will be tens to hundreds of square degrees at the binary merger for the Advanced LIGO-Virgo detector network. We show that radio observatories, e.g., MWA and ASKAP, with their capability of prompt response and large field of view, have an advantage in that they cover the large sky area of GW source sky position error boxes, while breakthrough science is more likely with high-energy gamma-ray experiments such as Fermi and Swift as well as optical telescopes such as ZTF. We demonstrate that the opportunity to catch EM flashes around binary merger can be enhanced by further speeding up the detection pipelines of both GW observatories and EM follow-up facilities.

In the second part of the talk, we propose a new model of binary mergers within hierarchical triples, where the star in the outer orbit is accreting onto an inner binary composed of a pair of compact objects [2]. The physical mechanism is similar to the accretion-driven coalescence of binary supermassive black holes. For binary black holes accreting from a high-mass star, we show that the accretion flow could possibly drive the inner binary to merge much faster than it would purely due to gravitational radiation. We argue that this could greatly enhance the event rate of these binary mergers and make it comparable to binary mergers from “normal” channels and thus could be an important source of GWs. Such triple-driven binary mergers are particularly interesting from an EM point of view, since they are expected to be associated with matter outflows and possibly relativistic jets, and the source of plasma near the merging black holes could permit amplification of magnetic fields and coherent relativistic plasma emission. The presence of the third body could be observed from gravitational waves alone, due to its acceleration of the inner binary, in greatest details for many sources that would be detected by eLISA a few years before they enter the LIGO band. We therefore expect these binary black hole mergers to be of multi-wavelength nature as those high-mass X-ray binaries, and LIGO and eLISA will help provide a wealth of information about the system.

Reference:

[1] Chu, Q., Howell, E.J., Rowlinson, A., Gao, H., Zhang, B., Tingay, S. J., Boër, M., Wen, L. 2016, MNRAS, 459, 121
[2] Wen, L., Phinney, S. and Chen, Y. 2016, in prep.

Notes

Challenging science missions utilizing very small satellites

Yoichi Yatsu
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We have been working on developing micro-satellites in cooperating with Dept. of Space system engineering in Tokyo Tech. In this document, the history of our projects and the future missions are presented.

1. Introduction

In these years, dimensions of satellites are increasing owing to the progress of space technology. Therefore we can investigate faint and distant objects deeper than ever before. However the developing cost and time per satellite are also increasing. Moreover space missions are very risky still today. This situation can be the disadvantage of the challenging space science missions. In order to provide a breakthrough to the current situation, we have been developing very small satellites as a new platform for space science missions.

2. Cubesats

Since 2003, we had successfully launched three cubesats that are ultra small satellites below a few kg. The first one, "CUTE-I", is for demonstration of the satellite bus system developed with COTS devices. It must be noticed that CUTE-I is the one of the world first cubesat that worked in orbit. Then we planned utilizing cubesats as the platforms for demonstration and small experiments. For this purpose we developed Cute-1.7+APD (I/II) for the world first demonstration of avalanche-photodiodes (APDs) as radiation detector in space. Following our successful demonstration, *HXI* and *SGD* aboard "*Hitomi*" employed APDs for the active shield system (Fig 1).

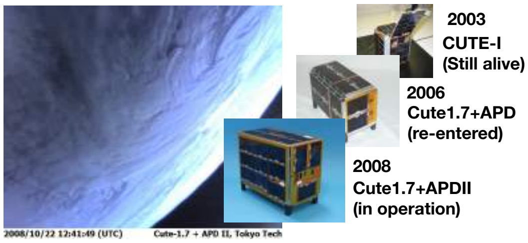

Figure 1. Tokyo Tech Cubesat projects

3. TSUBAME

The fourth satellite "*TSUBAME*" was designed for hard X-ray polarimetry of GRBs (Fig 2). To detect and localize the GRBs, the satellite has wide-field burst monitor (WBM) consists of five scintillation gamma-ray counters. When WBM detects a burst, its on-board computer calculates the coordinate of GRB within 2s after the detection. Then the satellite changes the attitude quickly and starts pointing observation with the polarimeter.

TSUBAME was launched on 2014 Nov 6th from Baikonur space center and injected into a polar orbit with an altitude of 500 km. The critical phase operation had seemed perfect. However we encountered fatal troubles in the RF receiver. We had continued recovery operation for three months, and finally lose signal on 2015 Jan 27th.

Figure 2. *TSUBAME* and Hard X-ray polarimeter.

4. Future mission

We are now planning the next satellite mission named "*Hibari*" for optical and near-UV (or IR) transient monitor. Potential targets are shock breakouts come before SNe, kilo-novae, and optical counterparts of gravitational wave sources. The satellite has a ø200mm telescope for near UV (or IR) telescope and two wide field optical monitors. The obtained data is processed with a high-performance OBC utilizing GPU for real-time transient detection. The subcomponent flight experiment is scheduled on 2017.

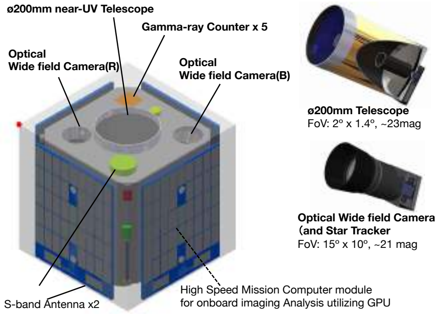

Figure 3. Optical Transient Explore "*Hibari*"

Session D: Relativistic Systems and Explosions

Talks

D1. The GHz Radio Transient Sky in the GW Era (Kunal Mooley)

D2. Supernovae driven by Relativistic Engines (Alessandra Corsi)

D3. Galactic Double Neutron Star Systems (Michael Kramer)

Contributed abstracts

D4. Mass loss in Luminous Blue Variables (Nadia Blagorodnova)

D5. Orphan Afterglows and Dirty Fireballs (Brad Cenko)

D6. Cosmic Explosions (Assaf Horesh)

D7. Constraining Substellar Magnetic Dynamos using Auroral Radio Emission (Melodie Kao)

D8. A Possible Counterjet in GRB 980703 (Dan Perley)

The GHz Radio Transient Sky in the GW Era

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Blind radio surveys have the exceptional ability to capture transients in dust-obscured environments, unbeamed and magnetically-driven phenomena, and offer unique discovery opportunities and strong diagnostics for cosmic transients. While a rich discovery phase space of transients has been revealed through synoptic experiments such as the Fermi Gamma-Ray Satellite, the Swift Gamma-Ray Burst Alert Mission, and optical imagers such as the CRTS, Pan-Starrs, and PTF, a similar yield awaits centimeter radio surveys. Most of what was known about slow radio transients (timescales >1s; supernovae, gamma-ray bursts, tidal disruption events, stellar flares, etc.) has come via radio follow-up of objects identified by synoptic telescopes at optical, X-ray or gamma-ray wavelengths. Until recently, radio interferometric searches for slow transients have been plagued by small fields of view, false positives, archival searches and untimely follow-up observations. As a result, the radio transient yield was extremely low and the transient rates and discovery phase space were poorly understood.

The ingredients for a successful survey (maximizing the chances for discovery and the detailed study of transients) for exploring the phase space of slow radio transients are: wide-field observations, near-real-time data processing, rapid transient search and multiwavelength follow-up with minimal lag. Thanks to the newly-commissioned On-the-Fly (OTFM; see Steven Myers talk) observing mode at the Jansky VLA, we have been able to implement these features as part of the Caltech-NRAO Stripe 82 Survey (CNSS). Carried out over 270 deg^2 of the Stripe 82 region in the S band (2–4 GHz) between December 2013 and May 2015, with 5 epochs and a sensitivity of 80 μJy/epoch, the CNSS is a benchmark survey dedicated for slow transient search. Notably, the CNSS is the first implementation of OTF mode for the Jansky VLA, a driver for the VLA Sky Survey, and one of the first systematic explorations of the dynamic radio sky on weeks-to-years timescales. The CNSS has revealed a rich variety of Galactic and extragalactic transients that would likely be missed at optical and X-ray frequencies.

At the same time, the CNSS has found low rates of radio transients and variables, revealing a GHz sky conducive for aLIGO counterpart searches. Thanks to the CNSS, we have a better understanding of the slow radio transients and will be able to sift through the false positive foreground to find the rare transients such as the mergers of black-hole/neutron star binary systems. We have commenced a program called JAGWAR for the blind search of aLIGO counterparts. We survey 100–200 deg^2 between 2–4 GHz typically in three epochs spaced by weeks–months. Our cadence is driven by the search for the orphan afterglow from the ultra-relativistic jet (on week∼month timescales) and the late-time afterglow from the sub-relativistic ejecta (on months∼year timescales). Given the false-positive contamination problem for finding kilonovae with optical surveys, our blind radio searches could prove to be better at finding aLIGO than the optical, especially for neutron star mergers in the disks of nearby galaxies or in dust-obscured hosts.

The curious reader can refer to Mooley et al. 2016 (ApJ, 818, 105) for more details.

Notes

Supernovae driven by Relativistic Engines
(with applications to radio follow-up of gravitational waves)

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Broad-lined supernovae of type Ic (BL-Ic SNe) are a rare form of massive stellar deaths that provide us with a special window into the rarer-still engine-driven explosions known as long duration gamma-ray bursts (GRBs). Like ordinary SNe of type Ib/c, BL-Ic events result from naked cores which have been stripped of their hydrogen (type Ib), and possibly helium (type Ic), envelopes before the explosion. However, in SNe Ic with broad lines the photospheric velocities can be as high as 0.1c, and the inferred kinetic energies can be an order of magnitude larger than the canonical 10^{51} ergs. This points to an engine-driven explosion, i.e. a stellar death with an extra source of energy, perhaps imparted from a GRB jet or extracted from a newly-born GRB-magnetar. However, not all BL-Ic SNe are associated with GRBs, and what makes some stars die as ordinary BL-Ic SNe and some others launch relativistic jets remains a mystery.

The link between BL-Ic SNe and GRBs was first made for GRB 980425 and SN 1998bw, which showed strong radio emission (peaking at $t \approx 20\,\mathrm{d}$ since explosion at 5 GHz) indicative of relativistic expansion. During the years 1998-2010 (a dozen years since the identification of the radio bright SN 1998bw), only a few other reliable GRB-SN associations were identified. For all of these associations, the SN was of the exotic *BL-Ic type*. In spite of this important observational fact, the fraction of BL-Ic SNe harboring GRBs was left largely unconstrained due to the very small number of *purely BL-Ic events* with radio follow-up available to the community. In addition, although a key prediction of the jet model for GRBs is that some SNe should be associated with "off-axis" GRB jets (highly-relativistic, collimated ejecta initially pointing away from the observer's line-of-sight), almost 20 years after the discovery of GRB afterglows we are still lacking the discovery of an off-axis jet.

Motivated by the above considerations, in the last 5 years we have been systematically following-up BL-Ic SNe with the Karl G. Jansky Very Large Array (VLA). This project has been enabled by the much-increased rate of BL-Ic discoveries provided by the Palomar Transient Factory (PTF) and more recently by the intermediate PTF (iPTF). Radio is indeed the best wavelength to look for signatures of engine-driven explosions. Past observations have shown that Ib/c SNe associated with relativistic ejecta are "radio bright" and sit, in terms of GHz-radio luminosity, in between "radio dim" BL-Ic SNe such as SN 2002ap, and "radio bright" ultra-relativistic GRBs observed on-axis. Off-axis GRB emission should also peak in the radio band at late times, when the ejecta slow down and spread intersecting the observer's line of sight. We have thus combined early- and late-time VLA follow-up observations of a sample of iPTF BL-Ic SNe to search for these signatures, and set the first observational upper-limit on the fraction of BL-Ic SNe harboring GRB jets. Our sample of BL-Ic SNe with radio follow-up doubles the one collected by the community over more than a decade.

Finally, the experience gained by the study of radio bright BL-SNe is helping us with follow-up strategies for electromagnetic counterparts of gravitational waves. Because radio traces the most relativistic explosions and because the transient radio sky is quieter than the optical one, the VLA working in tandem with the iPTF/ZTF can help pinpoint electromagnetic counterparts to gravitational waves among the many optical transients expected to be found in a typical LIGO/Virgo trigger localization area (tens to hundreds of square degrees). During Advanced LIGO first observing run (O1), we have demonstrated the feasibility of iPTF+VLA follow-ups and our findings are key to optimizing the electromagnetic follow-up campaign of future LIGO-Virgo triggers.

For more information about this project, see: http://adsabs.harvard.edu/abs/2015arXiv151201303C and http://adsabs.harvard.edu/abs/2016ApJ...824L..24K.

Notes

Galactic Double Neutron Star Systems

Michael Kramer – MPI für Radioastronomie

Double neutron star systems (DNSs) are rare objects. They are often also difficult to find but they are also extremely useful for providing insight for a number of science topics. In the standard scenario, DNS systems begin as two high-mass stars in a binary orbit. The higher-mass star will undergo a supernova explosion resulting in a neutron star with high-mass companion. During a period of mass transfer from the companion onto the neutron star, causing the latter to become mildly recycled, the system can be detected as a high-mass X-ray binary. Eventually, the companion will also undergo a supernova explosion, leaving behind a second neutron star. In the rare case that the system survives both supernovae and the resulting kicks, the result is a DNS.

If the final orbit is compact enough, pulsar timing allows the precise measurements of a number of relativistic effects, which can used for tests of general relativity (GR) and alternative theories of gravity under strong-field conditions. These tests include radiative tests as well as, for instance, tests relating to the properties of spacetime (e.g. Shapiro delay, geodetic precession). A key result of these measurements is also the precise determination of neutron star masses, which in turn, combined with the precisely known orbital parameters, allows us to draw conclusions about the birth events and properties of neutron stars.

Currently, about 15 DNSs are known, including neutron stars with masses ranging from $1.17M_{sun}$ to $1.56M_{sun}$ - the latter actually combined in one rather asymmetric system as presented by Martinez et al. (2015, ApJ, 812, 143), who also provide a recent list of known systems. The most compact system, the Double Pulsar, provides the most precise test of GR's quadrupolar gravitational wave radiation (see Figure) and is also on track of providing the first measurement of the moment-of-intertia of a neutron star via a measurement of Lense-Thirring precession. In order to achieve this measurement, which will be extremely important for identifying the equation-of-state of super-dense matter, further high precision timing measurements are required. These will be greatly facilitated by new radio facilities, especially the SKA Precursor telescope MeerKAT in South Africa.

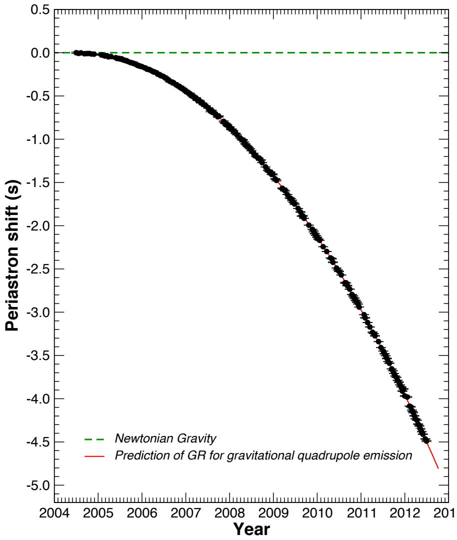

Figure: Accumulated shift of periastron time due to gravitational wave emission in the Double Pulsar (Kramer et al. in prep.)

Other new facilities like FAST will also contribute enormously to the study of DNSs, thanks their much-improved sensitivity[1]. Searches with these telescopes will also uncover more Galactic DNS, providing a much better understanding of the DNS population, and hence, of compact systems in general. The resulting improved merger rates can be compared with the upcoming DNS-merger signals to be detected with LIGO, allowing us to assess our understanding of the formation of these systems across different cosmic windows. Most intriguingly, however, we can expect the discovery of even more, even more exciting DNS systems. This talk will summarize the latest results, the latest tests of general relativity including the discovery of new effects, as well as highlights from recent DNS searches. Finally, an outlook on the prospects enabled by new upcoming instruments is given.

Suggested further reading:

- Lorimer & Kramer, Handbook of pulsar astronomy, CUP (2005)
- Özel & Freire, ARAA, 2016arXiv160302698O (2016)
- Lorimer, http://relativity.livingreviews.org/Articles/lrr-2008-8/

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[1] Although in this case, FAST will sadly "miss" the Double Pulsar due to its declination limit

Notes

Mass loss in Luminous Blue Variables - evidence for a hidden companion?

Nadejda Blagorodnova, Caltech

Traditionally, dramatic episodes of mass loss in massive stellar systems come in two different flavours: single and double. On the one hand, the luminous end ($M_{\rm Bol} = -9.5$ mag) of the Hertzsprung-Russell (HR) diagram hosts a population of stars known as Luminous Blue Variables (LBV) (Humphreys & Davidson 1994). Some known LBVs in the LMC, such as R127 and S Doradus (Wolf 1989; Walborn et al. 2008, and references therein) have shown non-periodic variability consistent with minor episodes of mass loss. However, sometimes these stars also exhibit major non-terminal outbursts, similar to the ones in Eta Carinae and P Cygni. The visual changes in magnitude are generally >2 mag and the mass loss rates are in the regime of $10^{-5} - 10^{-4}\ \dot{M}\ {\rm yr}^{-1}$. The origin of such episodes still remains unclear.

On the other hand, evolution in binary systems are expected to dominate in the massive stellar end (∼ 80%; Kobulnicky & Fryer 2007; Sana et al. 2012). About ∼ 30% of cases are expected to be close enough to allow interaction between the companions before ending their lives as Supernovae (de Mink et al. 2014). The mass transfer between the binary components gives place to a wide variety of phenomena, e.g. thermonuclear supernovae, luminous red novae, cataclysmic variables, stripped core collapse supernovae and millisecond pulsars. Binarity is also an important channel for the generation of close massive black hole systems, such as the ones detected by LIGO (Abbot et. al. 2016).

Recent radio observations of nearby LBV: R127 and HR Car, have suggested a possible connection between these two classes of events. R127, initially observed as part of a larger set in (Agliozzo et. al. 2012), already showed evidence of a bimodal emission component (see Figure 1). Follow-up observations obtained with ALMA and ATCA provided a strong evidence for a polar mass loss scenario, likely associated to a presence of a companion, rather than asymmetries in the mass loss (Agliozzo et. al. in prep). Similar conclusion were derived from the multi-wavelength dataset on HR Car (Buffano et. al. in prep), including high-resolution images from mid- and far-IR to radio wavelengths. The data showed strong evidence of gas-dust interaction, originated in the complex morphology of the LBV nebulae. The geometry of the emitting material also suggested the possibility of a lower mass companion, which could be responsible for some of the major mass loss episodes.

One possibility to investigate further the connection between major episodes of mass loss in massive stars and the existence of low mass companions would involve a survey in radio wavelengths, targeting close LBV. Maps taken at multiple frequencies will reveal the morphologies of the nebulae. Along with high resolution images in Hα and IR wavelengths, these observations would allow us to reconstruct the mass loss history for the more massive stars, uncovering the possibility of a past merger events or interaction with an undetected companion.

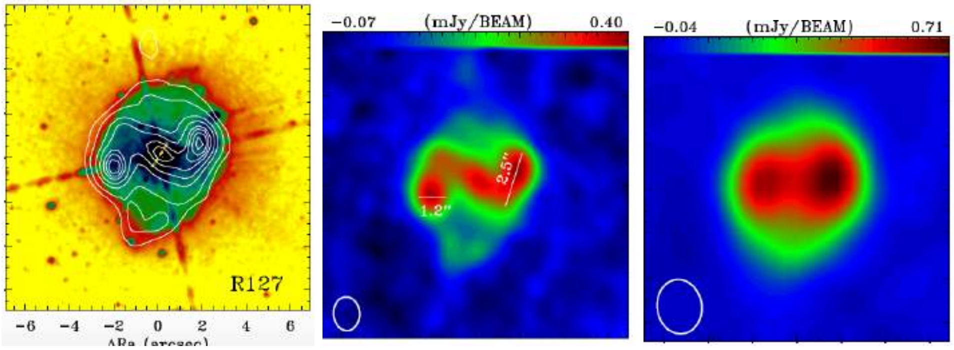

Figure 1: Figure from Agliozzo et. al. 2012. It shows the LBV R127 in the SCM observed using the Hα, 5.5 and 9 GHz contours obtained with the Australia Telescope Compact Array (ATCA). A bipolar structure suggests an asymmetric mass loss in the equatorial plane of the star.

Orphan Afterglows and Dirty Fireballs — S. Bradley Cenko (NASA/GSFC)

Two central tenets of our standard model of long-duration gamma-ray bursts (GRBs) hold that these explosions are ultrarelativistic ($\Gamma_0 \gtrsim 100$) and highly collimated (biconical jets with half-opening angle $\theta \approx 1$–$10°$). In order to accelerate material to these velocities, the outgoing jet must entrain a very small amount of mass ($M_{\rm ej} \approx 10^{-5}\,{\rm M}_\odot$); this is referred to as the "baryon loading" of the jet. Most *observed* GRB prompt spectra, with peak spectral energies of a few hundred keV, therefore indicate very "clean" outflows (i.e., low mass of entrained baryons). But there is growing evidence that the intrinsic population of long GRBs is dominated by bursts with peak energies below the traditional γ-ray bandpass. Could these lower $E_{\rm pk}$, fainter outbursts (e.g., X-ray flashes) result from an outflow with more entrained mass (i.e., a "dirty" fireball)?

Separately, the high degree of collimation requires that most ($f_b \equiv (1-\cos\langle\theta\rangle)^{-1} \approx 100$) GRBs are beamed away from Earth. The afterglows of these off-axis bursts become visible at late times when the outflow slows down and illuminates an increasing fraction of the sky. Yet despite concerted efforts at uncovering such orphan afterglows in the X-ray, optical, and radio bandpasses, no *bona fide* off-axis candidate has been identified thus far.

For the last several years, I have led efforts to identify relativistic explosions *independent* of any high-energy trigger with the Intermediate Palomar Transient Factory. This has resulted in the first unambiguous example of a GRB afterglow discovered independent of a high-energy trigger (iPTF14yb; Cenko et al., ApJL, 803, 24, 2015), as well as a possible example of a relativistic outburst lacking high-energy emission entirely (PTF11agg; Cenko et al., ApJ, 769, 130, 2013). Radio follow-up will of such discoveries in the Zwicky Transient Facility (ZTF) era will play a key role in establishing the Lorentz factor and viewing geometry of these sources (expected event rate $\approx 5\,{\rm yr}^{-1}$). On the other hand, orphan GRBs may well be discovered for the first time in upcoming wide-field radio surveys, where a close coupling to optical and high-energy missions will be critical for robust classification.

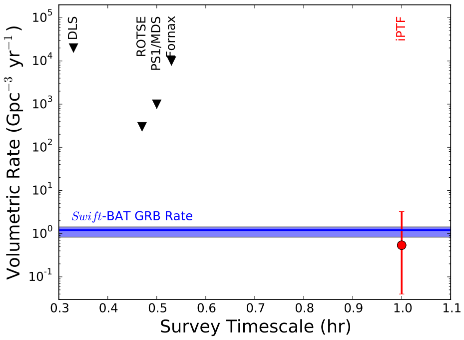

Figure 1: *Rate of fast, luminous optical transients, from iPTF and other surveys, compared to the rate of on-axis long-duration GRBs. With iPTF we are sufficiently sensitive for the first time to detect GRB afterglows **independent of any high-energy trigger***

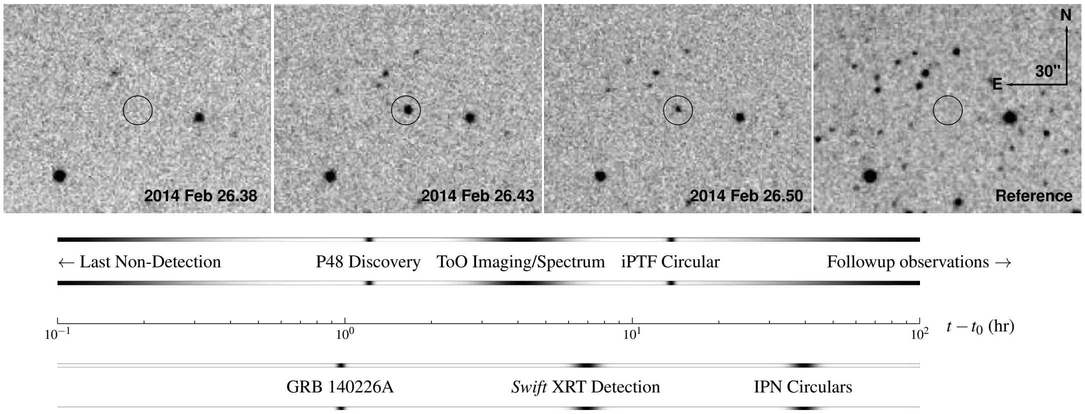

Figure 2: *Top: P48 discovery images of iPTF14yb. The circle marks the location of iPTF14yb. Bottom: Timeline of iPTF14yb/GRB 140226A discovery and announcements.*

Assaf Horesh (Weizmann Institute of Science → Hebrew University of Jerusalem)

Cosmic Explosions

The past seven years have seen tremendous activity in the study of supernovae (SNe) and other violent transients in the universe, thanks to the introduction of a generation of wide-field optical transient surveys including PTF, Pan-STARRS, and SkyMapper. These surveys operate in the optical band, but a panchromatic picture is required to capitalize on them.

Death of Massive Stars - Studying the Final Epoch of Stellar Evolution - Understanding the different evolutionary paths of massive stars leading to the different types of supernovae (SNe) is an important open question, involving the physics of massive star evolution (including mass loss, rotation, and binary interactions) and that of core collapse and shock-driven explosions. It is therefore very desirable to be able to constrain this connection observationally. Optical emission from a typical SN is dominated by thermal emission from the expanding photosphere or recombination of ionized ejecta, revealing the temperature and chemistry of the ejecta but saying little about the material surrounding the star or about the ejection of additional high-velocity, optically-thin material in front of the photosphere. In contrast, radio observations trace high-energy particles, magnetic fields, and the interaction of fast outflows with the surrounding medium unveiling these hidden components and helping to establish the identity of the stellar progenitor.

Circumstellar matter (CSM) provides both a robust and critical view of the progenitors of supernovae. The gross attributes of the progenitor stars (mass, radius and composition) are determined by their mass loss history. These stars can explode with a modest mass loss (type II supernovae) to significant mass loss (type Ib, Helium composition; type Ic, carbon composition). More extreme examples have come to our notice: SN 2009ip (Mauerhan et al. 2013) and PTF 10tel (Ofek et al. 2013) show spectacular and substantial ejections as short as a month prior to the supernova explosion.

Currently, we are conducting followup radio observations of transients discovered by PTF (and iPTF). An example of the importance of radio observations is SN2011dh, a type IIb SN in the nearby M51. We undertook prompt major radio campaign to observe this nascent SN with both VLA and CARMA (Horesh et al. 2013a). Our dataset now constitute some of the earliest and systematic radio observations of core collapse SNe. The early observations were crucial to measure the full radio spectrum. The observations yielded the CSM density, magnetic field, and the shockwave velocity at small radius. Through this campaign we have shown that type IIb SNe do not necessarily originate from a distinct population of either compact or very extended progenitors, as was suggested before, but in fact they originate from a continues population of progenitor sizes. Moreover, our combined radio/optical/X-ray analysis has shown that the blast wave largely deviates from equipartition, a result which has an effect on our understanding of shockwave physics.

Another intriguing result is the identification of "fast" radio SNe. Our mm- and cm-wave observations of PTF 12gzk, a Type Ic SN, showed that the emission from this SN have faded quickly within ~ 10 days. The analysis of our data points out to a high ejecta velocity of $\sim 0.3\,c$. Therefore, this SN is considered an intermediate event connecting ordinary Type Ib/c SNe (with low ejecta velocities) with relativistic Type Ic SN that are associated with GRBs (Horesh et al. 2013b). A future campaign of prompt radio observations following early SN detections may uncover a whole population of this type of "fast" radio transients, which remained mostly unexplored so far.

Type Ia Supernovae - At the other end, Type Ia SNe have been argued to arise from either a single degenerate white dwarf (WD) system or a binary one (WD-WD). A detection of significant interstellar medium may disfavor models in which supernovae result from coalescence of two white dwarfs (which undoubtedly take place; cf, Maoz et al. 2012). We have undertaken the earliest and most sensitive radio observations of a Type Ia supernova to date (SN 2011fe; Horesh et al. 2012). Our analysis showed that a large subset of single degenerate models can be ruled out.

The emerging picture from Type Ia studies is that probably a large fraction of Type Ia SNe originate from binary WD-WD systems. However, it is not clear if other channels indeed exists and if so how often do they occur. In fact, several claims have been made, based on optical spectra, that $\sim 20\%$ of Type Ia SNe have signature of significant CSM. We intend to address this question by targeting specifically this type of CSM-Ia SNe.

New Classes of Explosions - Over the last few years new classes of explosions have been identified. The *Swift* satellite has contributed handsomely to the field. Swift J1644, is the first time the onset of a non-thermal tidal disruption event (NTDE) was observed. Our radio observations of a sample of optical TDEs show that some TDEs will not form relativistic jets as in the case of Swift J1644 and are purely thermal. Another new class is ultra-long GRBs (Levan et al. 2013). These events exhibit very long prompt gamma-ray emission (≥ 1000 s) followed by late-time X-ray afterglow which, unlike other long GRB afterglows, shows flaring activity as late as 10^4 s after the initial burst. In our study of the latest event in this class, GRB130925A, we found that its radio spectrum is extremely unusual (Horesh et al. 2015). The steep spectrum cut-off indicates a steep electron energy distribution that requires an alternative particle acceleration mechanism. The latest new type of transient that we have studied is the first kilonova that has been discovered, GRB 130603B (Tanvir et al. 2013; Berger et al. 2013). This event is believed to be the result of a coalescence of two Neutron stars. Some predictions suggest that in this type of compact binary merger, a magnetar will form. However, via our late-time VLA observations of this event, we were able to rule out this scenario (Horesh et al. 2016).

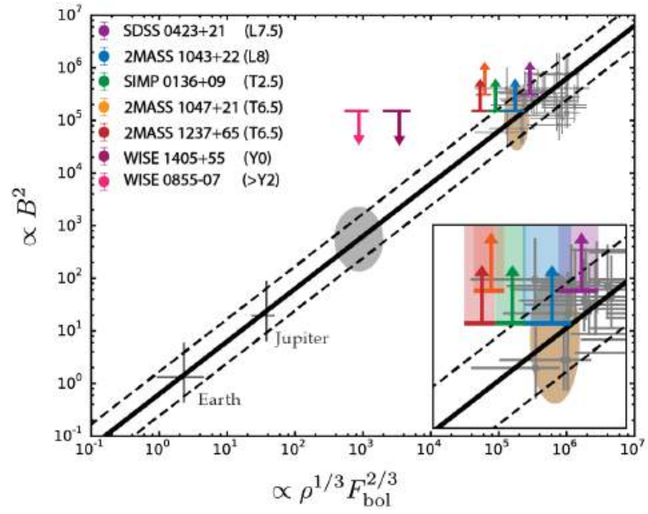

FIG. 1.— Updated from Kao et al. (2016). Reproduction of Figure 2 from Christensen et al. (2009), showing their proposed dynamo scaling relation with 3σ uncertainties for fully convective, rapidly rotating objects (black solid line and dashed lines, respectively). Grey points represent T Tauri stars and old M dwarfs. The brown ellipse indicates predictions for a 1500 K brown dwarf and the grey ellipse for a 7 M_J exoplanet. Our targets are overplotted, with upward and downward arrows to indicate lower or upper bounds. Horizontal bars indicate estimated uncertainties. The inset shows more clearly our estimated uncertainties. We adopt minimum surface field strengths of 2.5 kG and 3.6 kG for objects detected at 4–8 GHz and 8–12 GHz, respectively. For 2MASS 10475385+2124234, we adopt 3.6 kG as measured by Williams & Berger (2015).

Constraining Substellar Magnetic Dynamos using Auroral Radio Emission

Melodie M. Kao (mkao@caltech.edu)

An important outstanding problem in dynamo theory is understanding how magnetic fields are generated and sustained in fully convective objects. A number of models for possible dynamo mechanisms in this regime have been proposed but constraining data on magnetic field strengths and topologies across a wide range of mass, age, rotation rate, and temperature are sorely lacking, particularly for brown dwarfs. Detections of highly circularly polarized pulsed radio emission provide our only window into magnetic field measurements for objects in the ultracool brown dwarf regime. However, these detections are very rare; previous radio surveys encompassing ∼60 L6 or later targets have yielded only one detection.

We have developed a selection strategy for biasing survey targets based on possible optical and infrared tracers of auroral activity (Kao et al. 2016). Using our selection strategy, we previously observed six L7–T6.5 dwarfs with the JVLA at 4–6 GHz and detected the presence of highly circularly polarized auroral radio emission for five targets. I developed a method for comparing magnetic field measurements derived from auroral radio emission to those derived from Zeeman broadening and Zeeman Doppler imaging. Our initial detections provided the most robust constraints on dynamo theory in this regime, confirming magnetic fields >2.5 kG and providing tentative evidence that the dynamo operating in this mass regime may be inconsistent with predicted values from currently in vogue models. This suggests that parameters beyond convective flux may influence magnetic field generation in brown dwarfs (Fig 1).

To further our understanding of magnetic fields in brown dwarfs, we observed two Y-dwarfs at 4–8 GHz, both with tentative non-detections that provide upper limits to surface magnetic fields <2.5 kG (Kao et al. in prep). We additionally extended initial observations of the detected L/T dwarfs to 8–12 GHz, which corresponds to ∼3.6 kG fields. Initial analysis confirms radio emission at these higher frequencies in the L6/T2 binary, SDSS 04234858-0414035, with forthcoming results from the other objects.

Finally, to study the importance of rotation in dynamo physics, our higher frequency observations have time coverage sufficient to measure the first cloud-independent rotation periods for late L and T dwarfs. These period measurements will complement my ongoing 4–8 GHz survey of 33 brown dwarfs ranging in spectral type L2.5–Y0 and rotation periods 1.4–13 hours.

A Possible Counterjet in GRB 980703

Daniel A. Perley
Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen

GRB 980703 was one of the best-studied gamma-ray bursts before the launch of Swift, in particular at radio frequencies. After a possible jet break ∼5 days after the burst and subsequent steep decline, the radio light curve showed a flattening at all wavelengths between t = 1–3 years, previously interpreted (by Berger et al. 2001 and Frail et al. 2003) as being due to an ultraluminous host galaxy. We recently used the Jansky Very Large Array to obtain ultra-late-time (>15 years) re-observations of this event and several other pre-Swift gamma-ray bursts with purported late-time host detections in the radio. We found that the radio counterpart of GRB 980703 has faded significantly, ruling out that the host galaxy is responsible for the earlier flattening. Instead, this behavior may have been due to a counterjet, directed 180 degrees away from the line of sight and containing similar energy as the forward jet. The peak time, flux, and spectral index inferred from the data are all in good agreement with theoretical predictions for this model. Alternative models can also explain the data, but are less favored on physical grounds. Detection of a counterjet would confirm that GRB radio afterglows can be detected highly off-axis, and will represent an important contribution to future radio transient surveys.

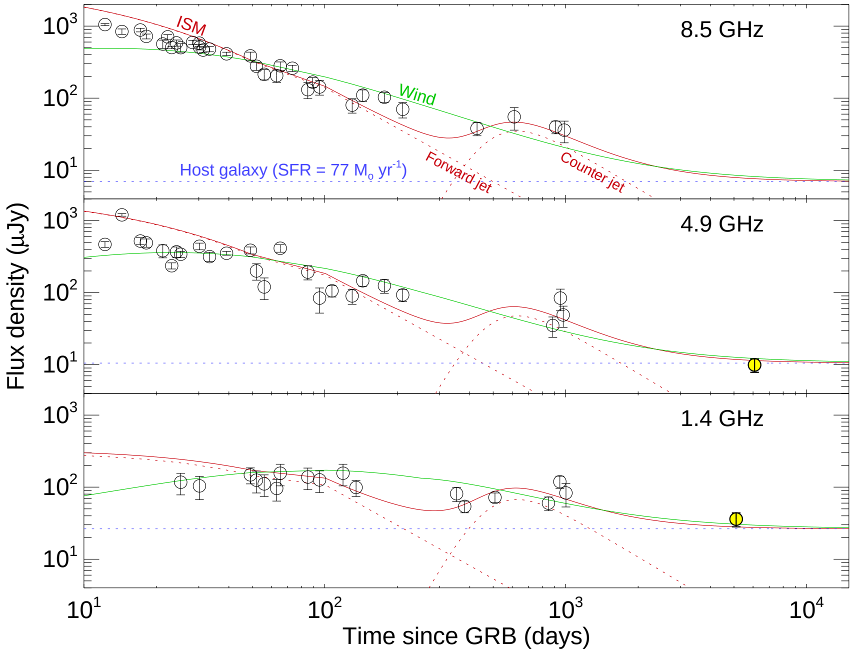

Figure 1: Multi-frequency radio light curve of GRB 980703. Data points from Frail et al. 2001 are shown as unfilled symbols; our new late-time VLA observations are highlighted in yellow. The solid red curve shows a model light curve for a forward shock expanding into a dense constant-density medium and experiencing an early jet break at ∼5 days, including emission from a counterjet 180 degrees off-axis. An alternative model showing expansion into a wind-stratified medium is also shown (green). The blue dotted line shows the contribution from the host galaxy, which we now believe to be a (non-ultra) luminous infrared galaxy with a star-formation rate of $77 M_\odot$ yr $^{-1}$. The 5 GHz light curve shows strong interstellar scintillation at <100 days.

Sessions E and F: Transients

Talks

E1. Transient searches with LOFAR (Dario Carbone)

E2. Transients: MWA (Steve Croft)

E3. The OVRO LWA (Gregg Hallinan)

E4. CASPER Religion and Philosophy (Dan Werthimer)

F1. Galactic X-Ray Binaries (Greg Sivakoff)

F2. Nuclear Radio Transients (Kate Alexander)

Contributed abstracts

EF1. An Unprecedented Window on the Radio Transient Sky (Marin Anderson)

Transient Searches with LOFAR

Dario Carbone[1]

The Low Frequency Array (LOFAR) is a new generation radio interferometer operating between 20 and 240 MHz. It is built mainly in the Netherlands, but has stations in other European countries as well, providing a maximum baseline of about 1500 km. LOFAR is constituted of two different arrays, operating below and above the FM radio band. The Low Band Antennae (LBAs) are sensitive between 20 and 80 MHz, while the High Band Antennae (HBAs) are working at 110 to 240 MHz. In the last years several projects have been carried out using LOFAR to detect transient and variable sources both in the image plane and in beam-formed time series data. In this talk I will focus on image plane transient searches. LOFAR is a digitally pointed radio interferometer that allows observations in multiple directions at the same time. This feature is very useful for transient searches as it allows monitoring of large parts of the sky simultaneously.

The observing strategy that has been optimised for transient searches includes 11-minute snapshots of the target field(s) plus 2-minute observations of a calibrator source. This strategy allows us to have good calibration solutions, and have sensitivity at multiple timescales. In fact, with this strategy we have observations of the same field starting every 15 minutes (2 minutes are required for re-pointing the telescope). Typical LOFAR images produced in this way have a field of view of $\sim 15\,\mathrm{deg}^2$, a sensitivity of ~ 100 mJy and a resolution of ~ 1 arcmin.

Once images have been produced, they are run through the Transient Pipeline (TraP, Swinbank et al., 2015) in order to detect if any transient or variable source is present in our dataset. This pipeline is also used by other projects nowadays, such as VLITE, LWA and AARTFAAC. The main steps the TraP performs are quality control (in order to remove bad images), source extraction and association (in order to build light curves of the sources), variability analysis (in order to detect transient and variable sources).

I will present the main results of the transient surveys performed with LOFAR, including the discovery of the first transient detected by this instrument, ILT J225347+862146 (Stewart et al. 2016), and the independent rediscovery of the redback pulsar PSR J2215+5135 (Broderick et al., 2015). I will also discuss that the low frequency radio sky has so far been proven to be far less rich in transient and variable sources than expected. I will present new methods that have been developed to set the most accurate and stringent upper limits to the transient rate taking into account both the flux and the duration of the transients (Carbone et al., 2016). I will conclude presenting a method to simulate transient sources and their detectability from a given survey strategy. Such technique is independent of the type of source and of the survey that is used, and allows me to set upper limits on (in case of non detection), or calculate the value of (in case of the detection), the transient rate for any combination of flux and duration of the transient.

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Transients: MWA

Steve Croft, David Kaplan, and the MWA Transients Collaboration

A new generation of high-throughput telescopes is coming online. Designed to maximize survey speed, they create images, catalogs, and spectra of the "static" sky, but also probe the time axis by comparing multiple epochs. Whether operating in a blind survey mode, or responding rapidly to triggers from across the electromagnetic spectrum (and beyond), these instruments have the combination of field-of-view and sensitivity to find sources rare or absent in earlier studies.

The Murchison Widefield Array (Tingay et al. 2013), situated in the West Australian outback, is the Square Kilometre Array precursor telescope at low frequencies. The MWA consists of 2048 dual-polarization dipole antennas optimized for the 80–300 MHz frequency range. The antennas are arranged as 128 tiles, each of which is a 4×4 array of dipoles. The array has no moving parts, as all telescope functions including pointing are performed by electronic manipulation of the dipole signals. Analog beamforming narrows the FOV to a fully steerable $\sim$600 deg^2 at 150 MHz. The majority of the tiles are located across a $\sim$1.5 km region (with outliers out to 3 km, and, after the ongoing Phase II expansion is completed, out to 6 km), forming an array with very high PSF quality that images the full tile FOV at a resolution of several arcminutes.

Currently, the MWA is able to image the full field with 31 MHz bandwidth every 0.5 s, producing full-polarization images. In 0.5 s the 5σ detection threshold is $\sim$ 500 mJy; over 5 min we can reach $5\sigma \sim 50$ mJy in Stokes I, limited by confusion. In circular polarization, where many transients are bright, the limit is substantially lower.

Our work (e.g. Rowlinson et al. 2016) has been instrumental in pushing the search for blind transients into new regions of transient rate — sensitivity space. Although the radio transient sky, particularly at low frequencies, is not as replete with transients as some of the more optimistic early predictions, we are close to the region in which known classes of sources are expected to lie, and recently detected a promising transient candidate (Murphy et al., submitted; Fig. 1). However, we can also take advantage of the capabilities of the MWA to search for radio counterparts to a wide range of high-energy transient phenomena. Followup of known sources dramatically limits data volume and complexity allowing for much more rapid turn-around and more sensitive searches.

Recent triggered observations have included: a search for prompt radio emission from the short GRB 150424A, where we began collecting data 23 s after the X-rays hit *Swift* (Kaplan et al. 2015), providing the deepest and fastest limits to date on any GRB; searches for counterparts to high-energy astrophysical neutrinos from ANTARES (Croft et al. 2016), placing new constraints on progenitor models; and fast-response follow-up of a variety of other triggers, including LIGO events.

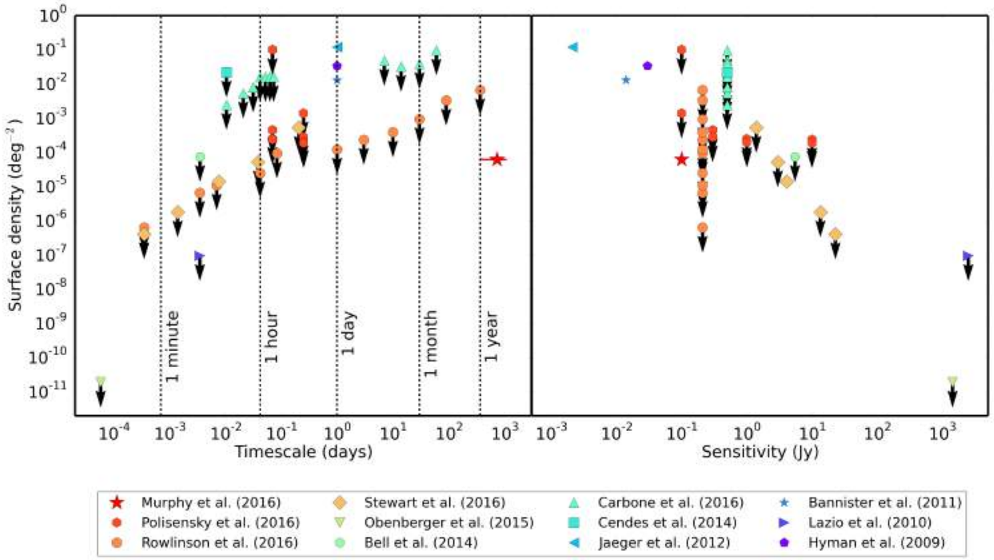


Figure 1: Limits (Murphy et al. 2016) on transient rates from comparison of the MWA GLEAM and GMRT-TGSS surveys (red star) compared to previously published results at low frequency ($<$ 1 GHz).

Notes

Gregg Hallinan: The OVRO-LWA

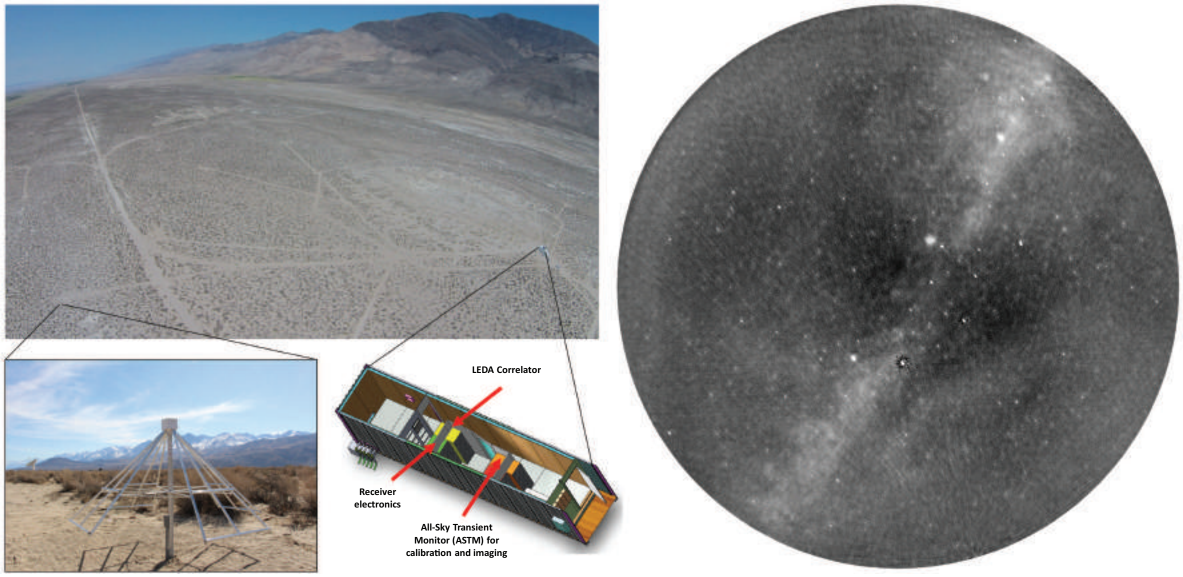


Figure 1. ***Left:*** *An aerial shot of the OVRO-LWA outlining the signal path and spatial extent of the array, with cut-outs shown of the LWA antenna and electronics shelter.* ***Right:*** *A single 9-second integration at 60 MHz, using* $\sim$ *15 MHz bandwidth, detects* $> 10^3$ *sources, largely dominated by the extragalactic AGN population.*

The Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA) is an ongoing project to develop an array that can image the entire viewable sky at frequencies $24-82$ MHz, with time resolution of a few seconds, and spatial resolution of 5 arcminutes. The full array, when complete, will consist of 352 dual-polarization antennas, spanning a 2.5 km diameter area. 251 of these antennas will be packed tightly together in a dense core of 200 m diameter, with the remaining 101 outlier antennas spaced over the 2.5 km diameter area, in a non-redundant configuration optimized for high fidelity imaging. The array is serviced by the LEDA correlator, which provides full cross-correlation of 58 MHz bandwidth (2400 channels) for 512 inputs (to be upgraded to 704 inputs), enabling instantaneous snapshot imaging of the entire viewable sky. To date, 288 of the antennas have been installed, with the construction of the final 64 antennas to begin in late 2016.

The all-sky capability of the OVRO-LWA is optimized for targeting the low frequency radio transient sky, as well as characterizing the IGM at high redshift (Cosmic Dawn: $z \sim 15-20$) and the monitoring of solar and Jovian radio emission. Recent results from LOFAR, as well as previous results from archival VLA data at 330 MHz, suggest that populations of unidentified radio transients do indeed exist at low radio frequencies. However, while searching for such transients is a key goal for the OVRO-LWA, its main function as a transient machine will be to monitor ~ 3000 nearby stellar systems out to ~ 25 pc in the search for “extrasolar space weather”.

Studies of young solar analogs have demonstrated that the enhanced magnetic activity of the zero-age main sequence Sun, powered by its rapid rotation, was a major factor in defining the atmospheric properties of the terrestrial solar system planets. This was recently demonstrated in dramatic fashion by the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission, which confirmed that ion loss due to solar coronal mass ejections (CMEs) early in Mars history likely severely depleted its atmosphere. The presence of a stronger planetary magnetosphere may have prevented a similar process occurring on Earth. Extrapolating to the exoplanet population, the impact of stellar magnetic activity on planetary atmospheres, and the importance of planetary magnetic fields in negating such activity, may redefine habitability, particularly for the M dwarf population. However, no CME on a star other than the Sun has ever been detected. Similarly, direct detection of planetary magnetic fields has yet to be achieved and remains the most crucial ingredient in assessing planetary habitability in the context of stellar activity. Both stellar CMEs and planetary magnetic fields can be probed via extremely bright radio emission at low radio frequencies. The detection of exoplanets is particularly significant, as it allows accurate measurement of their magnetic fields for the first time. However, the extreme space weather events that produce such bright radio bursts are rare, motivating the all-sky capability of the OVRO-LWA for near continuous monitoring of 1000s of stellar systems.

Notes

CASPER Religion and Philosophy:

How to Rapidly Build Cheap Powerful Digital Instrumentation for Boutique Experiments

Dan Werthimer[1], 1000 CASPER Collaborators, and Eight Million SETI@home collaborators
[1]University of California, Berkeley danw@SSL.berkeley.edu

The Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) collaboration has developed open source hardware, software, GPUware, gateware, and architectures for rapid development of high performance digital radio astronomy instrumentation. Even mere astronomers can design and build digital backend instrumentation for their boutique experiments after about week of learning via the CASPER tutorials or attending a CASPER workshop.

CASPER instrumentation is utilized at hundreds of observatories, universities, and government labs, mostly for radio astronomy, but also for physics, medicine, genomics and engineering.
I will review some of the new hardware and software developments from the collaboration, including new FPGA and ADC boards, and open source designs for correlators, beamformers, spectrometers, pulsar, FRB, VLBI, and SETI instruments. I will discuss how CASPER has developed flexible general purpose heterogeneous instruments that are scalable, upgradeable, and fault tolerant, using terabit/second ethernet switches and industry standard protocols.
I’ll also speculate on what kind of instruments the radio astronomy community could build in 10 and 20 years.

I'll also talk a bit about how boutique experimenters can utilize volunteer computing to analyze their data using the Berkeley Open Infrastructure for Network Computing (BOINC) infrastructure. (eg: SETI@home, Astropulse, Einstein@home,...), and how some of these technologies are revolutionizing SETI.

Open source hardware, software, libraries, tools, tutorials, training videos, reference designs, and information on how to join the collaboration are available at http://casper.berkeley.edu
BOINC information is at http://boinc.berkeley.edu

Notes

Galactic X-Ray Binaries:
Radio “Experiment” Techniques with Wider Applications

Gregory R. Sivakoff (University of Alberta) on behalf of many collaborators

In X-ray binaries material from a nearby companion star accretes onto a compact object (neutron star or black hole) through a disk. In some accretion states, there are jets of material that move away from the compact object at relativistic speeds. Many X-ray binaries undergo relatively brief periods of intense accretion, separated by longer periods of quiescent accretion. These transient systems vary on timescales of seconds to years, allowing for time-resolved studies of entire outbursts. Thus, X-ray binaries, especially Galactic sources, deeply probe the connected evolution of accretion disks and relativistic jets, and act as lower-mass (and highly accessible) analogues to Active Galactic Nuclei. Although some of the techniques described below have been utilized in the past, upgraded instrument and modes of collaboration are allowing these techniques to be employed more readily (and in tandem). Moreover the lessons learned utilizing these techniques have wider applications for both “boutique surveys” and “experiments”.

Going higher — Under standard models of relativistic jets, higher frequency observations of the compact steady jet (the jet-type associated with the non-thermal accretion state of X-ray binaries) probe jet properties closer to where the relativistic particles in the jet are first accelerated. Thus millimeter and sub-millimeter (mm/sub-mm) observations not only probe closer to the strong gravitational environment of black holes and neutron stars, but also probe inherently smaller size scales (assuming an expanding jet). With upgrades to mm/sub-mm facilities, a couple of relativistic jets brighter than about 1–5 mJy in X-ray binaries are being observed every year. When the Atacama Large Millimeter/submillimeter Array becomes more strongly responsive to Target of Opportunity observations, larger number of these sources could be observed. The evolving mm/sub-mm fluxes or some X-ray binaries constrains jet properties like their radiative power.

Supersizing science with sub-arrays — The recent upgrade to the Karl G. Jansky Very Large Array (VLA) has enabled sub-array observations, where the VLA can be broken up into 2 or 3 completely separate interferometric arrays. Although each sub-array is less sensitive than the full VLA, Galactic X-ray binary observations are increasingly using subarrays to simultaneously measure the spectral index of jets over wide ranges of frequencies. Moreover, there are several other advantages for X-ray binaries (and other sources that are sufficiently bright or evolve rapidly!). Shorter scheduling blocks, shorter integration times, observations uninterrupted by calibrations concerns, and efficient mosaicing can all be achieved with sub-arrays.

Simultaneity is more than the sum of its parts — Past X-ray binary observations across the electromagnetic spectrum could be separated by days before being combined to form a single spectral energy distribution; however, non-simultaneity affected interpretation. While more X-ray binary observations are being performed quasi-simultaneously, strictly simultaneous observations are becoming increasingly important for rapidly evolving transients — even our definition of “simultaneous” may be up for grabs.

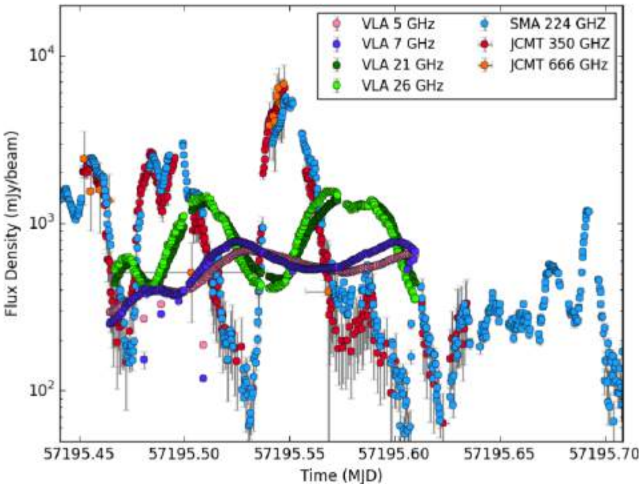


Figure from Alexandria Tetarenko et al. (2015, ATel #7708; 2016, in prep) Radio/mm/sub-mm light curves from the 2015 outburst of the black hole X-ray binary V404 Cygni. These data show the benefits of combining all of the above techniques. The higher frequency data probe the behaviour of the relativistic jet closer to the black hole. With sub-array observations using the VLA, we measure the simultaneous light curve at four radio frequencies. The lower frequency observations are smoothed and delayed versions of the higher frequency data. We are using these data to probe jet physics in new ways, adapting Van der Laan (1966) models to the case of an expanding, bi-symmetric, pair of relativistic bubbles with geometric time delays.

Notes

Nuclear Radio Transients

Kate D. Alexander

Active galactic nuclei, powered by long-term accretion onto supermassive black holes (SMBH), produce relativistic jets with lifetimes of $\gtrsim 10^6$ years (Begelman et al. 1984), which makes observations during the birth or cessation of jet activity highly unlikely. In contrast, transient accretion onto an SMBH through the tidal disruption of a stray star (Hills 1975; Rees 1988) offers a unique opportunity to study the birth and cessation of jet activity, as well as to probe the environment around previously-dormant SMBHs and to discover lower mass SMBHs than with existing techniques ($\sim 10^4 - 10^7$ $M_\odot$).

The primary signature of a tidal disruption event (TDE) was long predicted to be transient optical/UV/soft X-ray emission from the newly-formed accretion disk (e.g., Rees 1988). However, the discovery of the unusual γ-ray transient *Swift* J164449.3+573451 (hereafter Sw 1644+57), revolutionized our view of TDEs. This event was the first TDE with a jetted relativistic outflow that produced strong γ-ray, X-ray, and radio emission (Bloom et al. 2011; Burrows et al. 2011; Levan et al. 2011; Zauderer et al. 2011). The radio emission, discovered and extensively studied by our group, allowed us to: (i) localize the transient to the very center of an inactive galaxy at $z = 0.354$ and hence support its TDE origin; (ii) determine the properties of the relativistic outflow (energy, size, expansion velocity); and (iii) trace the ambient density profile around the SMBH on a scale of $\sim 0.1 - 10$ pc, which is not otherwise accessible for any SMBH outside of Sgr A* (Zauderer et al. 2011; Berger et al. 2012; Zauderer et al. 2013).

Following the discovery of Sw 1644+57, another jetted TDE with radio emission was found, Sw 2058+0516 (Cenko et al. 2012). Motivated by the *Swift* TDEs, several groups have undertaken late-time radio observations of X-ray and optically-selected TDEs from the past $10 - 20$ years (Bower et al. 2013; van Velzen et al. 2013; Arcavi et al. 2014; Chornock et al. 2014). These have mostly resulted in non-detections, although recently a serendipitously discovered X-ray and radio flare has been modeled successfully as a TDE with an off-axis relativistic jet similar to the *Swift* events (Irwin et al. 2015; Lei et al. 2016). The current observational sample indicates that at most $\sim 10\%$ of all TDEs produce relativistic jets (van Velzen et al. 2013; Mimica et al 2015). One of the primary goals of current radio studies of TDEs is thus to constrain the requirements for jet formation.

Recently, our group discovered evidence for a second type of outflows from TDEs. Using the Very Large Array, we searched for and detected transient radio emission from the $z = 0.021$ optically-selected TDE ASASSN-14li, arising from a non-relativistic outflow (Alexander et al. 2016). Our result provides the first line of evidence that γ-ray emission does not accompany all outflows from TDEs, and that radio emission is a more ubiquitous signature of mass ejection. Interestingly, ASASSN-14li straddles the boundary between sub- and super-Eddington accretion, indicating that outflows do not necessarily require the most extreme mass accretion rates. ASASSN-14li is several orders of magnitude less radio-luminous than Sw J1644+57 and the radio emission is below the level of previous upper limits set by radio non-detections of other optical/UV selected TDEs. While ASASSN-14li is the first optical TDE with detected radio emission, it is therefore possible that these types of outflows are ubiquitous among TDEs. Further observations of nearby TDEs are needed to explore this possibility and determine the preconditions necessary to launch non-relativistic outflows.

In this talk, I will give an overview of the status of TDE radio observations, highlighting insights from our ongoing followup of Sw J1644+57 and ASASSN-14li. I will also briefly discuss future prospects for the field. With the increasing number of TDE discoveries from several wide-field optical surveys and from *Swift*, the time is ripe for deep radio follow-up of new events at both early and late times to constrain the jet formation process (Coughlin & Begelman 2014; Tchekhovskoy et al. 2014), understand the origin of non-relativistic outflows (Strubbe & Quataert 2009; Lodato & Rossi 2011; Krolik et al. 2016), and study the circumnuclear environment in TDE host galaxies (Generozov et al. 2016).

Notes

An Unprecedented Window on the Radio Transient Sky

Marin M. Anderson (Caltech)

The hunt for extrasolar space weather with the OVRO-LWA. The Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA) is a new low frequency facility operating from $24-84$ MHz, optimally designed for the monitoring and characterization of extrasolar space weather events associated with stellar and planetary magnetic activity. Full cross-correlation of 256 dipoles over maximum baselines of 1.5 km provide a full-sky field-of-view with $\mathcal{O}(10)$ arcminute resolution.

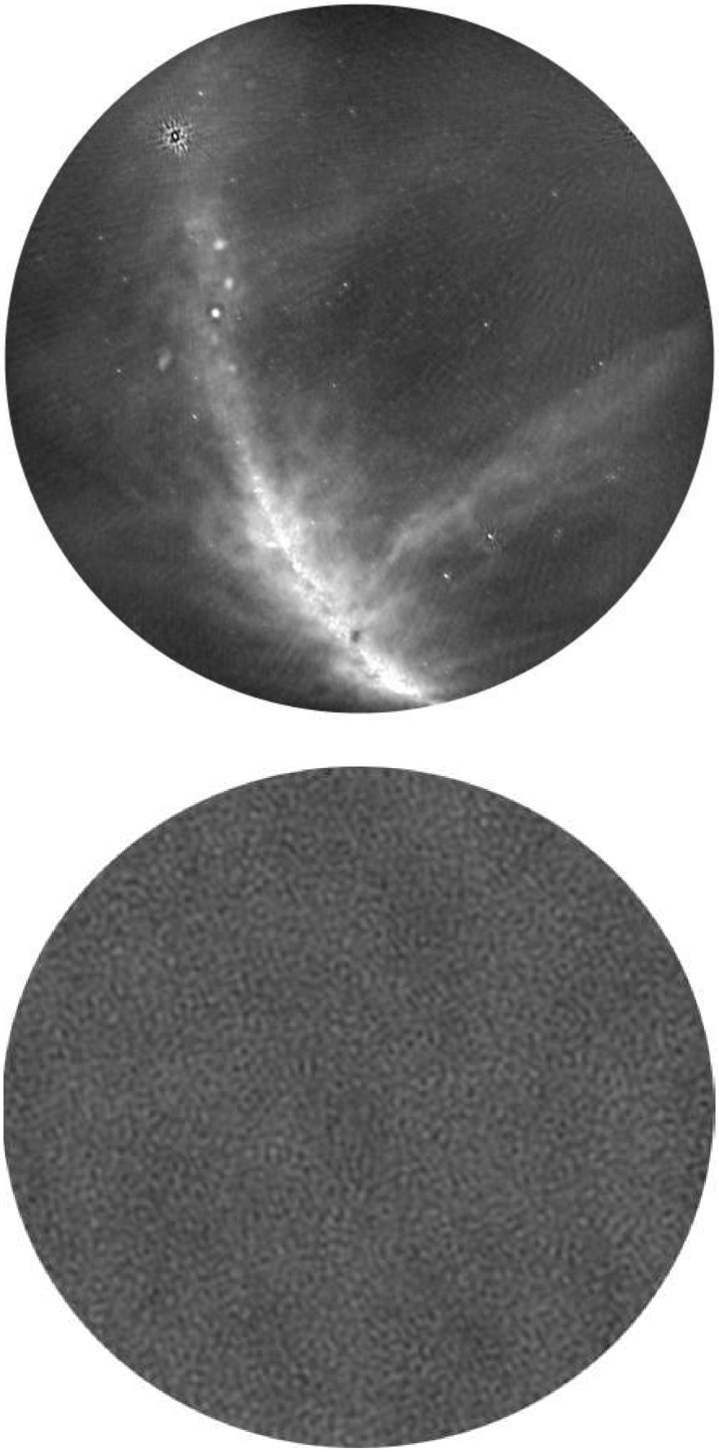
Our growing understanding of the history of the solar system demonstrates the importance of stellar magnetic activity and planetary magnetic fields in redefining planetary habitability. Magnetic field strengths of exoplanets can be directly measured from the detection of their auroral radio emission, but as yet no confirmed detections of planetary radio emission outside of our solar system exist. Wide-field, long-duration surveys with the capability of monitoring thousands of objects simultaneously are needed to detect these rare transient events in which planetary radio emission brightens substantially during extreme coronal mass ejection (CME) events from the host star.

I am conducting the largest survey for planetary radio emission to date, monitoring thousands of stellar and low-mass objects within 25 pc with the OVRO-LWA, which can continuously image the entire viewable sky at high cadence (13-second cadence over 100 hours) to search for transient phenomena, particularly the low frequency radio bursts associated with extrasolar space weather events such as stellar CMEs and planetary aurorae. **The OVRO-LWA is uniquely positioned to monitor extrasolar space weather events, compared to previous surveys attempting to detect planetary radio emission, due to the following:**

- **Full-sky field of view and continuous imaging:** We are able to monitor thousands of systems simultaneously and over complete rotation periods. This large sample allows us to both overcome geometric selection effects due to emission beaming and detect rare CME-associated events.
- **60 MHz of instantaneous bandwidth below 100 MHz:** Planetary radio emission frequencies scale with magnetic field strength, requiring wide bandwidth at low frequencies to detect Jupiter-like objects.
- **Stokes V imaging:** To push below the confusion noise limiting Stokes I surveys, I am developing the polarization calibration for the OVRO-LWA that will enable us to conduct our search for (highly circularly polarized) planetary radio emission in Stokes V. The sky is virtually empty of Stokes V emission, drastically improving our sensitivity below 100s of mJy.

The cm-λ sky with the JVLA: VLAFast and the Caltech-NRAO Stripe 82 Survey (CNSS) CNSS is a dedicated radio transient survey at 3 GHz with the Jansky Very Large Array (JVLA), targeting the extragalactic explosive afterglow population. It was conducted over five epochs with a maximum separation of 1.5 years, and covered the 270 square-degree SDSS Stripe 82 field. Near real-time calibration, imaging, source extraction, and transient identification pipelines were developed to enable triggering of rapid multi-wavelength follow-up of detected transients (Mooley et al. 2016). CNSS successfully demonstrated many of the techniques that are now integral to the ongoing VLA Sky Survey (VLASS).

CNSS, in combination with pre-existing archival JVLA data, is part of the VLAFast survey, a search for fast radio bursts (FRBs) in 1000 hours of image data at 1 and 3 GHz. In light of the results by Vedantham et al. 2016 showing a flatter than Euclidean $\log N$-$\log F$ distribution for FRBs, VLAFast, once completed, promises to either place strong constraints on the all-sky rate or contribute the much-needed detection of an FRB by an interferometer.



An all-sky, 13-second snapshot from the OVRO-LWA at 50 MHz, using ∼60 MHz bandwidth. **Top:** Stokes I image, showing the galaxy transiting and thousands of extragalactic point sources. **Bottom:** Corresponding Stokes V image for a single subband, entirely devoid of sources. Searching in Stokes V for transient exoplanetary radio emission completely removes the haystack from the needle.

Introducing Marshall Cohen

A. C. S. Readhead

Marshall Cohen, an early participant in radio astronomy, has always been a pioneer irrespective of the field he is working in. Marshall's work encompasses the polarization of solar radio flares, diffraction in irregular media, interplanetary scintillations, the development of very long baseline interferometry, superluminal motion, active galactic nuclei, and optical polarimetry. In 1972 Marshal shared the Rumford prize for his pioneering work in VLBI.

In 1958 while at Cornell Marshall became closely involved in the plans for building the Arecibo Telescope in Puerto Rico, which was designed by Bill Gordon. At Cornell Marshall's work on solar polarized emission led him to consider propagation effects[1], and this led Marshall through the study of the hydrodynamic theory of plasma density fluctuations to electron density irregularities in the solar wind and interplanetary scintillation (IPS)[2]. Marshall managed to get Ed Salpeter interested in IPS as well and this led to a classic pair of papers – one on the theory of IPS by Salpeter and the other on the observations by Cohen et al (1966)[3].

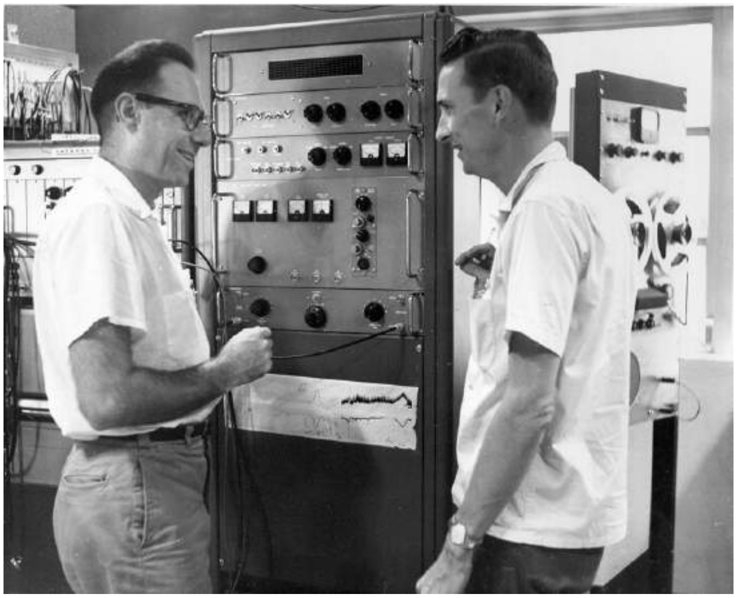
At the summer 1965 AAS meeting in Ann Arbor, Marshall and Ken Kellermann spent an evening working on a large pitcher of beer talking about interferometry. By time they were halfway through the pitcher, they had agreed that it would be possible to build an independent oscillator tape recording interferometer. Although they realized that all that was needed was a good stable oscillator and a broadband tape recorder, neither of them knew exactly how to actually implement it. When Ken got back to NRAO, he mentioned it to Barry Clarke and this led to the NRAO-CIT VLBI system[4].

The next year (1966) Marshall moved to UCSD for two years and then he went on to Caltech, where he established a very energetic VBLI group. In 1977 Marshall published a key review article on superluminal sources[5] in *Nature*, and he was the driving force behind the *Nature* paper on superluminal motion in 3C 273 using hybrid mapping[6]. Marshall formally retired in 1995. However, he continued his collaboration in the 15GHz VLBA survey of motions in AGN. This program has now become the MOJAVE (Monitoring Of Jets in Active Galactic Nuclei with VLBA Experiments) survey. Marshall continues to be an active member of this group writing first author papers[9,10].

A few years ahead of his retirement Marshall, foreseeing the imminent completion of the Keck 10-m telescope, decided to start an entirely new line of inquiry - optical polarimetry. Since typical polarizations are a few percent a large telescope is essential. Working together with graduate student A. Putney and R. Goodrich developed an optical polarimetric module for a workhorse spectrometer on Hale 5-m Telescope[7,8], and then they went on to develop a second optical polarimeteric module for the LRIS instrument on Keck Telescope.

Quite apart from the intellectual impact of his research Marshall has had a huge impact on radio astronomy in the US. In the mid-1970s Marshall organized the VLBI Network Users Group. Prior to this every VLBI run had to be set up completely ad hoc, but as a result of Marshall's leadership the community got together and committed set blocks of telescope time. This was a revolution in the field contributing greatly to its growth, efficiently, reliability and productivity. Another major impact Marshall had was in organizing the study for the "Transcontinental Radio Telescope" which led directly to the VLBA being chosen as a top priority in the Field Decadal Report.

[1] Cohen, 1961, ApJ, 133, 978 [2] Cohen, 1965 Nature, 208, 277 [3] Cohen et al. 1966 AJ, 71, 850 [4] Bare et al. 1967 Sci, 157, 189 [5] Cohen et al, 1977 Nature, 268, 405 [6] Pearson et al 1981 Nature, 290. 365 [7] Cohen, Putney & Goodrich, 1991, ApJ, 405, L67 [8] Goodrich & Cohen, 1992 ApJ, 391, 623 [9] Cohen et al 2014 ApJ, 787,151 [10] Cohen et al. 2015 ApJ, 803, 3



Top: M. Cohen with William Gordon at the Arecibo Observatory (circa early sixties). Bottom: The Caltech radio group, circa 1975.

IPS, VLBI, and ALFVEN WAVES

M. H. Cohen, Caltech

Interplanetary scintillations (IPS) were first systematically studied in 1962, at Cambridge. They are seen on compact sources as the Sun is approached. The scintillation index saturates and then is rapidly reduced when the source is inside a critical elongation, which depends on the source diameter. Thus the source diameter can be estimated from the run of index with elongation. This information also allows a study of the solar wind, subject to the reality of models. Studies of the interstellar plasma were also made, by assuming that angular diameters measured by IPS were the scattering angles induced by the interstellar medium.

IPS studies were started at the Arecibo Ionospheric Observatory as soon as practicable, after the news from Cambridge became public. At that time the square line feed (430 MHz) had high side lobes and accurate flux density measurements were impossible, However, relative measurements with a short time scale were feasible, and IPS (and lunar occulations) became major programs. The power spectrum of the scintillations was measured, and its shape, relative to that of a point source, determined the diameter. This works because, in the thin-screen, fixed-structure model for the solar wind, the diffraction pattern on the ground is the convolution of the point-source pattern and the source shape.

It is interesting that scintillation effects in the interplanetary plasma had been predicted in 1956, by analogy to the ionosphere, and IPS was searched for, unsuccessfully, in 1958. Rapid fluctuations were seen on Jupiter bursts in 1958, and IPS was later suggested as a possible mechanism, but these apparently went unnoticed. It remained for Margaret Clarke at the University of Cambridge to spot them in the interferometry records (178 MHz) that she was studying, Then, as now, it was difficult for most people to escape from their narrow specialties.

Very-long-baseline interferometry (VLBI) started soon after cheap and reliable atomic oscillators became available (Varian rubidium standards). Development programs started at the same time, 1965, in the USA and in Canada. The idea had been in the air, and the first publication about independent-oscillator interferometry was in 1965, several years after discussions in England and the Soviet Union, and, probably, Australia.

The major drivers for both the USA and Canadian programs was the fact that some sources were seen to be smaller than the best limits of the time, together with the accepted theory that required compact sources to have a very small angular diameter, of order 1 milli-arcsec. IPS was limited to a few mas, and lunar occultations to about 10 mas. Conventional interferometry was progressing towards 10 mas, but doing better was difficult, because extending baselines beyond about 100 km was beyond the state of the art. Independent oscillators was the key, and allowed the baselines to be more than the earth's radius. The first transcontinental measurements were in 1967, across Canada, to be quickly followed by observations from the US to Europe, Crimea, and Australia.

Caltech and OVRO played a large role in these early VLBI experiments. The 40-meter telescope was commissioned in 1968 and immediately participated in many experiments, first at 6 cm and then at both shorter and longer wavelengths as the equipment became available. Tapes from the telescopes had to be correlated after the observations were over, and that sometimes caused problems because errors could not be fixed. At first the correlations were done on a general-purpose computer, but in 1972 the first digital VLBI processor became available at NRAO. Multi-telescope experiments became the norm, and that of course led to processing backlogs. In the mid-70s Caltech and JPL began building a series of ever-larger processors that led to the 16-station processor in Robinson basement that accomodated most of the world's large experiments, for a number of years. Finally, in the late 1980s, NRAO built a dedicated VLBI system of 10 antennas (the VLBA), which recently was upgraded to 2 Gbps recording, giving 2800 times more bandwidth than the original USA digital system. Most university VLBI facilities were closed when the VLBA began operations.

In 1967-68 VLBI showed that many radio sources indeed did have sizes of 1 mas and smaller, confirming the theories and putting most of the IPS experiments out of business. Many varied results have since been obtained by VLBI, in geodesy and astrometry as well as in galactic rotation and studies of compact sources.

In keeping with the spirit of this conference, it should be noted that the early proposals for Arecibo were only a few pages long, and that the cost of the telescope was about $8 million. But that was 55 years ago. The original US VLBI program was funded with 2-page proposals to the Directors of NRAO and the Center for Space Research at Cornell. The first observations to the Crimea telescope were organized by writing letters to astronomers we knew in the Soviet Union, although we found out later that both the CIA and the Soviet equivalent spent a lot of time going over the possibilities before issuing the appropriate licenses.

However, it should also be noted that the expensive and highly organized VLBA has allowed synoptic observations to be made, giving high-quality images of many AGN in a routine way. This has opened the door to many studies that could not have been made in the old days. For example, high-cadence observations of BL Lac have revealed superluminal patterns in the jet that have been identified as Alfvén waves, and show that the jet behaves like a relativistic whip.

The 1972 Rumford symposium. In addition to Marshall Cohen the following were present: Alan Rogers, Ken Kellerman, James Moran, James Condon, Geoffrey Burbidge, Peter Goldreich and Martin Rees.

Notes

Session G: Methodology

Talks

G1. Breakthrough Listen: SETI and beyond (Danny Price)

G2. The VLA Sky Survey (Steve Myers)

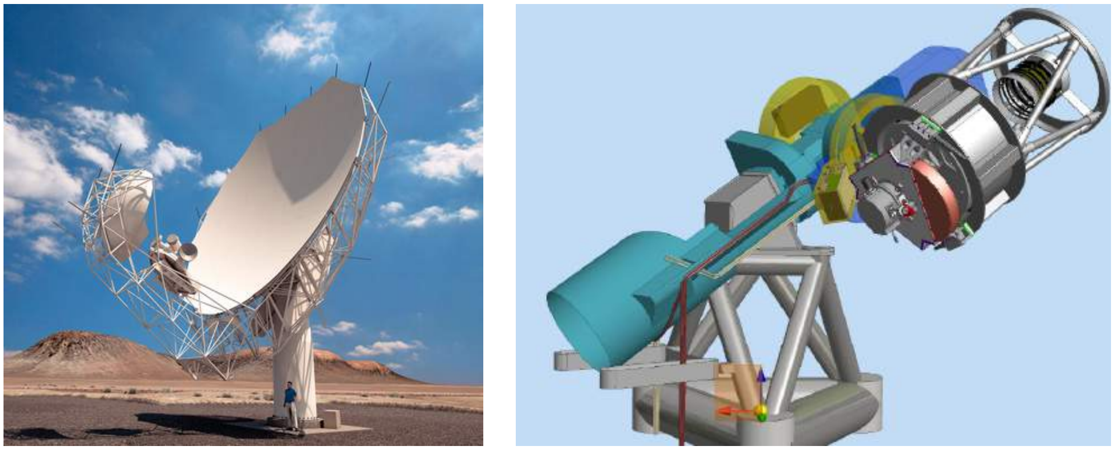
G3. MeerKAT & MeerLICHT: a status update (Paul Groot)

G4. Breakthrough algorithms (Barack Zackay)

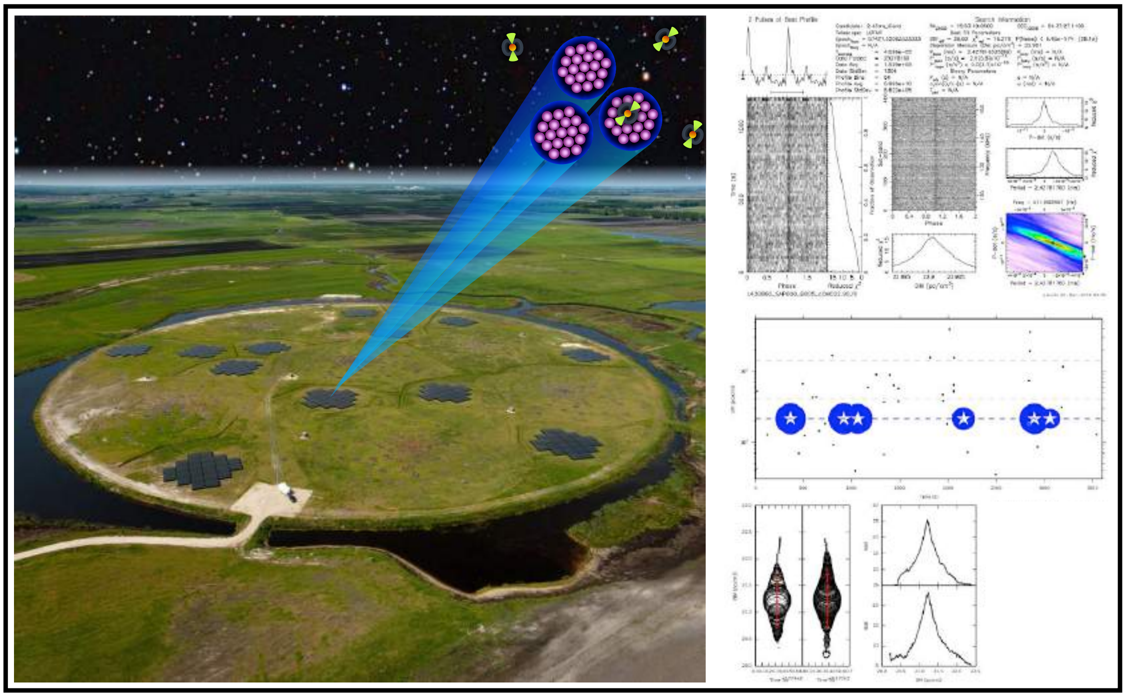
G5. Fast Transients with Arecibo and LOFAR (Jason Hessels)

Contributed abstracts

G6. Algorithms for the CHIME/FRB Search (Alex Josephy)



Co-observing between the MeerKAT radio telescope (the first dish is shown on the left) and the MeerLICHT 65 cm, 2.7 deg^2 FOV optical telescope (right) in a high-cadence optical imaging mode is slated to commence with the commissioning of MeerKAT-32. Figures from SKA-SA and P. Groot.



Left: The central core of the LOFAR array – the so-called "Superterp" – with an artist's conception of the digital multi-beaming mode that is used for pulsar and fast transient surveys. Right: the first millisecond pulsar (top panels) and rotating radio transient (bottom panels) discovered by LOFAR.

Breakthrough Listen: SETI and beyond

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Breakthrough Listen (seti.berkeley.edu) is a $100M, ten-year initiative to search for evidence of extraterrestrial intelligence (“SETI”) in a scientifically rigorous manner. The ultimate goal: to comprehensively answer whether or not we are alone in the nearby Universe. Breakthrough Listen (BL) is motivated by advances in capability of wide-bandwidth digital systems, and by the Kepler mission’s discovery that almost all stars harbor planetary systems and that the fraction of planetary systems with “habitable” planets (roughly one in five) are both much larger than was previously imagined.

A comprehensive radio-frequency SETI survey would observe over the entire radio window, from tens of megahertz to hundreds of gigahertz. Using the Parkes 64-m telescope and Green Bank 100-m telescopes, BL is surveying roughly 2000 of the nearest stars (a 50 light year range), covering all frequencies possible with the receiver suites available. In addition, surveys of the galactic plane and nearby galaxies will also be undertaken. New wide-bandwidth digital systems are being installed at both telescopes, to allow a band of up to 10 GHz wide to be recorded to disk. Each telescope will produce about a petabyte of raw voltage data each day; reduced data products will be made available to the public via an online data repository of several petabytes.

The BL radio surveys will be roughly 50 times more sensitive than previous surveys, and will cover the radio spectrum ~100 times faster than previous SETI search instruments. In comparison to our current technology, BL would be sensitive enough to detect extraterrestrial transmitters equal in equivalent isotropic radiated power (EIRP) to our own ubiquitous aircraft radars around the nearest 1000 stars. At the distance of the galactic center (~25,000 light years), the BL survey would be able to detect a signal with an EIRP 20 times that of the Arecibo interplanetary radar.

A longer-term goal, which will require new SETI instruments on the next-generation of radio telescopes, is to conduct deep observations on a million nearby stars. BL is also undertaking an optical SETI survey using the Lick Observatory 2.4-m Automated Planet Finder (APF) telescope. Development of an all-sky optical monitoring for SETI is currently being investigated.

The BL data archive will be one of the largest datasets within astronomy. Storing and processing these data poses challenges, but also presents opportunities for development of new processing approaches. Indeed, a revolution in data processing approach is required. Techniques from the big data and machine learning communities are being investigated as alternatives to the more “traditional” radio astronomy workflow and algorithms.

Of particular interest to this audience is the potential of extracting other science from the BL data. The reduced BL data products are both high spectral and high time resolution. There will opportunities to mine the data for spectral lines, fast radio bursts, pulsars and other transients. Given the volume and fidelity of the data, there may well be exotic and unexpected astrophysical phenomena waiting to be discovered.

Notes

The VLA Sky Survey

On-the-fly Mosaicking (OTFM) for efficient fast mapping of the sky and pipelines for rapid generation of Data Products

Steven T. Myers (NRAO)

The VLA Sky Survey (VLASS) will use the Karl G. Jansky Very Large Array (VLA) to cover 82% of the sky to a combined depth of 0.07mJy in the 2-4GHz S-band with an angular resolution of 2.5 arc-seconds. Each area of the survey will be observed in three epochs spaced by 32 months, each to a depth of 0.12mJy/beam rms per epoch, in order to investigate the transient radio source population over an unprecedented combination of depth and area, resulting in a uniquely powerful search for hidden explosions in the Universe. The survey will be carried out in full polarization, allowing the characterization of the cosmic magneto-ionic medium over a wide range of redshifts, and the study of Faraday rotating foregrounds such as ionized bubbles in the Milky Way. The high angular resolution will allow us to make unambiguous identifications of nearly 10 million radio sources, comprised of both extragalactic objects and more nearby radio sources in the Milky Way, through matching to wide area optical/IR surveys such as SDSS, zPTF, PanSTARRS, DES, LSST, EUCLID, WFIRST and WISE. Pilot observations for the VLASS have commenced in June 2016, with the 5400+ hour 7-year full survey starting in late 2017. The raw data will be available in the NRAO archive immediately with no proprietary period and science data products will be provided to the community in a timely manner.

The VLASS is possible due to the wide-bandwidth high sensitivity enhancements delivered by the Expanded Very Large Array project in 2010. To harness these capabilities for fast ultra-wide area surveys, we developed and implemented On-the-fly Mosaicking (OTFM) which allows data to be taken while the telescopes in the array are continuously scanning the sky (see Caltech PhD thesis by Kunal Mooley, 2015). Using wide-band OTFM, we can scan the sky to 0.12 mJy/beam rms over 2-4 GHz with a survey speed (excluding calibration and slewing overheads) of around 21 deg^2/hr. In order to produce a uniform survey at this depth, a number of challenges must be overcome, including mitigation of time and spatially varying radio-frequency interference (RFI) from terrestrial sources as well as from satellites. To prosecute the survey, the RFI identification and flagging, array calibration, and imaging must be carried out through automated processing pipelines. For the VLASS, these pipelines employ the CASA package. Current pilot pipeline benchmarks produce a complete set of “Quick-Look” continuum images within 72 hours of observation, on track to the ultimate goal of less than 48 hours. Integral to this workflow is maintaining Quality Assurance throughout the system from telescope to archive. These critical tasks are carried out by the VLASS team, which includes NRAO science operation staff as well as students, post-docs, and researchers from the community.

The VLASS Basic Data Products (BDP) that will be produced by the survey team include: raw and calibrated visibility data, quick-look continuum images, single-epoch images and spectral image cubes, single-epoch basic object catalogs, and cumulative static sky images and image cubes and basic object catalogs to the full survey depth. The storage and archive services budgeted for the BDP is around 1PB for the data and images combined. Significantly higher storage would be required to serve the highest spectral resolution spectral cubes over the full sky area, and thus devising an affordable strategy for providing these services is critical, for example through cloud-based Processing on Demand based on user query of the archive. There are also opportunities for community involvement in VLASS, including the development of Enhanced Data Products and Services that will greatly increase the scientific utility of the survey.

For more information on the VLA Sky Survey, see the VLASS web-site:
https://science.nrao.edu/science/surveys/vlass

Notes

MeerKAT & MeerLICHT: a status update

Paul Groot, Radboud University,
on behalf of the ThunderKAT, MeerLICHT and TRAPUM teams

The MeerKAT Radio Array

The MeerKAT Radio[1] is currently under construction at the SKA South Africa site. MeerKAT is a pre-cursor to SKA-1 Mid. It will consist of 64 dishes, each of a Gregorian design with 13.5m main reflectors. MeerKAT will have UHF, L-band and S-band receivers. The complete system is built in South Africa, and dish integration takes place on site. Currently, 16 dishes are on the ground and operations. Science operations are expected to start in the 1st Quarter 2017 with 32 dishes. Observing time on the MeerKAT array is largely distributed through Legacy Surveys (~70%) with the aim of ~30% open time. The Legacy Surveys have been defined and include a wide range of science cases, including Local Universe HI studies, pulsar timing, deep fields, the Fornax cluster, and both time-domain as well as image domain synoptic surveys.

The ThunderKAT and TRAPUM Legacy Surveys

The synoptic legacy surveys on MeerKAT are ThunderKAT[2] (PIs Woudt and Fender) for the image domain (slow) transients and TRAPUM[3] (PIs Stappers and Kramer) for the time domain (fast) transients. ThunderKAT has been granted commensal observing on all MeerKAT Legacy projects as well as Target-of-Opportunity overrides. Radio imaging will be done using a dedicated data pipeline which will be capable of a 1 second cadence. ThunderKAT science includes all transient and explosive phenomena, from jets in compact binaries to fast radio bursts, supernovae, gamma-ray bursts and gravitational wave sources. TRAPUM will run in timing mode with dedicated hours. The aim is to discover and study fast transients, including finding new pulsars, fast radio bursts and, possibly, gravitational wave counterparts. Both TRAPUM as well as ThunderKAT will start operation with the MeerKAT-32 dish array.

The MeerLICHT telescope: an optical – radio synoptic survey

Within the context of the ThunderKAT project the MeerLICHT[4] optical telescope was conceived for simultaneous optical observations of the MeerKAT fields. Besides a stand-alone telescope coupled to the MeerKAT array, MeerLICHT also serves as the prototype for the BlackGEM array of telescopes (to be installed at ESO La Silla in 2018). MeerLICHT is a wide-field Wynn-Harper-type optical telescope with a 65cm main mirror, providing a 2.7 square degree field-of-view sampled at 0.57”/pix using a 110 Mpix single STA1600 CCD detector. MeerLICHT will be equiped with a six-filter set of *u,g,r,i,z* and a wide-band *q* filter (440-720nm). MeerLICHT is a collaboration between Radboud University, the University of Cape Town, Oxford University, the University of Manchester, the University of Amsterdam and the national funding agencies of the Netherlands and South Africa, NWO and NRF, the last through the SAAO Observatory. MeerLICHT will be installed at the SAAO Sutherland station. MeerLICHT will always co-observe with MeerKAT in a sequence of *u,q,g,q,r,q,i,q,z,q,u,q*,... etc. with a 67s cadence between exposures (60s integration:*g*~20.5, 7 seconds read-out). MeerLICHT is currently being assembled at the NOVA optical-Infrared group and at Radboud University. Acceptance Europe is planned for X-mas 2016, shipment to South Africa over New Year 2017 and commissioning in 1st Quarter 2017. Start of operations will be simultaneous with MeerKAT-32.

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[1] www.ska.ac.za/meerKAT
[2] www.ast.uct.ac.za/thunderkat/
[3] www.trapum.org/
[4] www.ast.uct.ac.za/meerlicht/MeerLICHT.html

Notes

BREAKTHROUGH ALGORITHMS

Barak Zackay
Benoziyo Center for Astrophysics, Weizmann Institute of Science, 76100 Rehovot, Israel

Draft version July 13, 2016

ABSTRACT

Since the early days of radio astronomy, algorithms and high performance computing have played a crucial part in enabling scientific exploaration.

Pulsar astronomy, and the rising field of fast radio transients are two excellent examples for computationally limited sub-fields of radio astronomy.

In the Pulsar literature it was assumed that it is impossible to detect pulsars in binary systems on observation times longer than a fraction of the orbital period, as one has to blindly enumerate all options for the unknown 5 Keplerian parameters, the pulsar period, and the unknown DM to coherently process the entire data (e.g., Ng et.al 2015). Another example is the search for fast radio bursts, where even though their precise localization is crucial for the determination of their origin, radio interferometers were not extensively employed while searching for them due to computational limitations.

I will briefly present the Fast Dispersion Measure Transform (FDMT) algorithm (Zackay & Ofek 2014, arXiv:1411.5373), that allows to reduce the operation count in blind incoherent dedispersion by 2-3 orders of magnitude. Thus, FDMT removes a major bottleneck for searching FRB's using interferometers. In addition to it's importance for detecting FRB's, FDMT enables to probe the domain of extremely narrow astrophysical pulses ($\sim 10^{-7}\,$s) - See Zackay & Ofek 2014 (section 7) for more details. Albeit containing interesting sources (e.g., pulsar giant pulses), this phase space is currently unexplored.

Last, (given the limited amount of time) I will provide a preview to a novel algorithm that enables the detection of pulsars in short binary systems using long integration times (longer than an orbital period).

The state of the art techniques for detecting pulsars that are affected by orbital modulation are Fourier/time domain acceleration and jerk searches. In these searches, all the (sufficiently distinct) options for modulating the time series are enumerated, and after demodulating the time series with each option, a classical periodicity search in $O(n\log(n))$ time is employed. Indeed, a full blown keplerian orbit search using these techniques is impossible, as typically there are roughly $\sim 2^{110} \sim 10^{37}$ different options for the orbital modulation alone. Estimating the theoretical runtime for such an enumeration using all the computers on earth is longer than a hubble time. I will show, how to conduct such an enumeration, on a laptop, during the lecture, using real data of the double pulsar PSR_J0737-3039.

The algorithm for conducting such a search is radically different than existing pulsar search algorithms. It's main constituents are a dynamic programming extension of the Fast Folding analysis algorithm and an adaptive decision making algorithm, that exponentially narrows the phase space in which a statistically significant signal can reside in an adaptive fashion.

Example applications of this algorithm are:

1) Search for binary systems on an arbitrarily short Keplerian orbit using hours of integration time at maximal sensitivity.

2) Blindly search for all pulsars on all sky positions in Gamma ray observations of the Fermi LAT satellite, using very long coherent integration times.

3) Search blindly, with a long coherence time, for continuous gravitational wave sources, emitted by pulsars with non-axis-symmetric matter distribution.

Previous attempts to conduct all of the above searches contained substantial compromises reducing their sensitivity by more than an order of magnitude. We are currently using this algorithm on real data.

Notes

Fast Transients with Arecibo & LOFAR – Jason Hessels (ASTRON/U. of Amsterdam)

In terms of high-time-resolution (i.e. sub-second) transient radio astronomy, pulsars have ruled the skies for the last half-century. Even after so many years of intense study, their scientific impact remains huge because of the precision way in which they probe dense matter physics (Demorest et al. 2010, *Nature*, 467, 1081), strong gravity (Antoniadis et al. 2013, *Science*, 340, 448) and accretion (Archibald et al. 2015, *ApJ*, 807, 62). Pulsars are also precision probes of the intervening interstellar material via the effects of scintillation, scattering and Faraday rotation (Archibald et al. 2014, *ApJL*, 790, 22). But are pulsars the end of the story? Or are they just the tip of the iceberg of a much richer population of "fast radio transients"? The Fast Radio Bursts (FRBs) have generated a lot of excitement because they may address the above science cases in a way that pulsars could only dream of (though it may be the case that the FRBs *are* some type of exotic pulsar phenomenon). However, even with an event rate of many thousands of FRBs/sky/day, and our first example of an FRB repeater (Spitler et al. 2016, *Nature*, 531, 202), it has been frustratingly challenging to decipher their origin and realize their scientific promise of probing extreme environments and the intergalactic medium (Macquart et al. 2015, AASKA14, 55).

It's important to remember that radio pulsar and (most) FRB detections are strongly sensitivity limited: most new pulsar discoveries nowadays have flux densities of ~100 microJy at 1.4GHz and we're still seing just 10% of the expected Galactic population. Also, sufficiently sensitive radio telescopes probe only tiny fields of view: a 100-m class single-dish radio telescope sees only a hundreth of a square degree per pointing. Interferometers and focal plane arrays – assuming sufficient computing power at the backend – are starting to provide many square degrees per pointing, but we're still very far from having a "radio all-sky monitor" of sufficient sensitivity to be scientifically impactful and to complement such detectors in X-rays and gamma-rays.

With this as background, my talk will focus on two specific Boutiques/Experiments: i. Arecibo discovery and observations of the repeating FRB 121102 and ii. LOFAR searches for pulsars and fast transients.

FRB 121102 was discovered in the ongoing Arecibo PALFA survey (Spitler et al. 2014, *ApJ*, 790, 101), which is the deepest 1.4-GHz pulsar survey ever conducted (Lazarus et al. 2015, *ApJ*, 812, 81). The discovery of FRB 121102 and the fact that it *repeats* (Spitler et al. 2016) nicely illustrates that – in the quest for field of view – that sensitivity is still critical. In fact, though > 20 bursts have now been detected from FRB 121102 (Scholz et al. 2016, arXiv: 1603.08880) almost all these bursts are far too weak to have been seen by Parkes – the world's current FRB discovery record holder, which has 20 times the field of view of Arecibo. Whether FRB 121102 is like the other ~20 known FRBs is still unclear; those other sources have not been seen to repeat. In fact, FRB 121102 may even be a Galactic radio pulsar, though multi-wavelength observations show no evidence for unmodeled structures that could explain its high dispersion measure. I will present the latest results on this enigmatic source, including burst detections using full polarimetry and coherent dedispersion as well as our attempts to refine the position to sub-arcsecond precision using Arecibo as part of the European VLBI Network.

While Arecibo argues that sensitivity is key, wide field of view is also critical for opening discovery space for fast radio transients. In the second half of the talk I will present ongoing pulsar and fast transient searches with LOFAR at the low radio frequency of 135MHz. With the LOFAR "sparse aperture array" radio interferometer (van Haarlem et al. 2013, *A&A*, 556, 2), we can digitally form hundreds of fields of view simultaneously, allowing us to cover ~10 square degrees per pointing (Coenen et al. 2014, *A&A*, 570, 60). In the ongoing LOTAAS survey (http://www.astron.nl/lotaas) we have discovered 45 pulsars to date, including the first rotating radio transients (RRATs; McLaughlin et al. 2006, *Nature*, 439, 817) and millisecond pulsars found with an interferometer (also the first found at such low radio frequencies). In principal this huge field of view should also give great access to the FRB population (or other fast transients); however, to date no FRB has been seen below ~700MHz – suggesting that their detectability at low frequencies is hampered by (some combination of) intrinsic spectrum, scattering, and/or free-free absorption at the source. Knowing whether FRBs are at all detectable at low frequencies will provide an important insight into their physical nature and environment. Here's where FRB 121102 returns: we are now conducting simultaneous Arecibo and LOFAR observations of the repeating FRB to either detect bursts across the 100-2000MHz range or to set strong upper limits on the broad-band spectrum. At the same time, the discovery of RRATs (which are effectively low-DM FRBs) in the LOTAAS survey gives hope that LOFAR may still be the first low-frequency telescope to discover an FRB.

Notes

Algorithms for the CHIME/FRB Search

Alex Josephy (McGill Space Institute) on behalf of the CHIME/FRB collaboration

What follows is a summary of the algorithms that drive the dominant cluster of the CHIME/FRB pipeline. The sections are divided in relation to the principle task of the cluster-- dedispersion. My work has largely been concerned with development of the pre- and post-processing stages. For an overview of the entire CHIME/FRB project, see Keith Vanderlinde's extended abstract "CHIME as an FRB Machine".

Pre-processing: The input to the cluster is 8-bit intensity data at 1 ms cadence for 16384 frequency channels covering 400-800 MHz for 1024 pointings (~16 GB/s). To mitigate inter-channel smearing and improve sensitivity, a tunable pre-dedispersion may have been performed at a higher spectral resolution before the data enter the cluster. The main goal of pre-processing is to identify and remove radio frequency interference (RFI). For example, kurtosis and variance are employed to identify channels exhibiting non-Gaussian behaviour, red noise is mitigated with a high-pass filter, and zero-DM clipping may be used to remove broadband RFI.

Dedispersion: A brute-force approach of simply shifting and adding channels runs in $O(N_T \times N_f \times N_{DM})$ time, where N_T, N_f, and N_{DM} are the number of samples, frequency channels, and trial dispersion measures (DMs) respectively. By using a modified tree-like code called Bonsai, dedispersion is performed with cost $O(N_T \times N_{DM} \times \log_2 N_{DM})$. This reduction in complexity is incredibly important for making a CPU-based search over a large phase space possible. The phase space here is not limited to DM and pulse-width; spectral index and scattering measure are also incorporated into the matched filter of our search. The search configuration will be flexible to accommodate any emergent FRB population; as a starting place, we will search out to a DM of 10,000 cm^{-3}pc.

Another massive advantage of the Bonsai code is its ability to process input streams incrementally in small chunks. This is crucial for reducing the latency between reception and detection of a burst which allows the community to be alerted within seconds rather than minutes and minimizes the buffering required for the ~800 GB/s baseband dumps. Operating on cache-friendly sized chunks also gives substantial performance gains as dedispersion is limited by memory bandwidth.

Yet another boon to the Bonsai code lies in the treatment of dispersed bursts that are smeared across a different number of samples for different channels- a problem that is amplified by the large fractional bandwidth of CHIME. Unlike the brute-force case, Bonsai integrates samples in time according to the per-channel smearing. The result is a better recovered pulse and improved sensitivity.

Post-processing: After dedispersion, efficient peak-finding kernels utilizing Advanced Vector Extensions (AVX) instruction sets are applied. A dispersed pulse will appear over a range of DMs before it is broadened below the noise floor and these multiple detections need to be grouped together to produce a single candidate. Repeat detections over trial spectral index and scattering measure need to be grouped as well. The morphology of these groups is then inspected to make a decision on the likelihood that the detected peaks are the result of an astrophysical event or RFI. The most important feature is how the S/N of detections falls away at non-optimal DMs. A further sifting of RFI is done by coincident matching candidates across all beams. As a final note of potential interest, CHIME's daily scan of the sky adds another layer of detection potential as weak pulses will be logged and stacked to identify faintly repeating sources.

Session H: Radio Boutiques and Experiments

Talks

H1. Testing General Relativity with spacecraft Doppler tracking (Dmitry Duev)

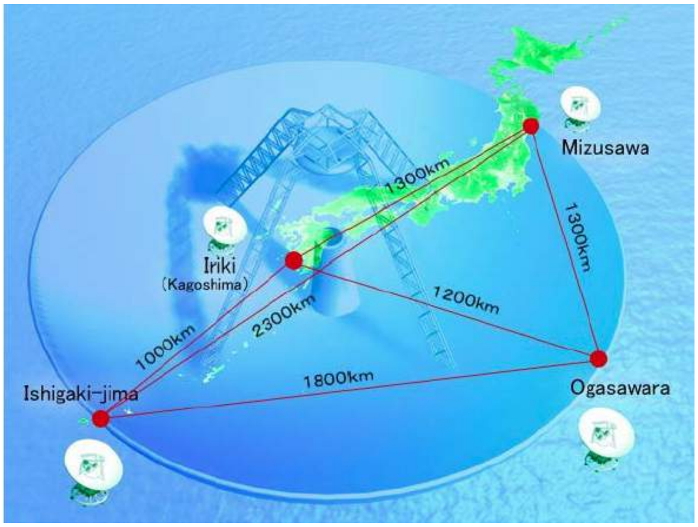
H2. The curious case of J1415+1320 (Harish Vedantham)

H3. Single dish & VLBI in Japan (Kenta Fujisawa)

H4. The Ecosystem of Radio Observatories (Dale Frail)

Contributed abstracts

H5. Radio – high-energy correlations in AGN variability (Tony Readhead)



Configuration of the 4 20 m antennas for the dedicated VERA VLBI array in Japan. Figure supplied by K. Fujisawa.

Testing General Relativity with spacecraft Doppler tracking

Dmitry A. Duev

California Institute of Technology, 1200 E California Blvd, Pasadena, CA 91125, USA

Precision Doppler tracking of deep space probes can be used for a number of scientific applications, both fundamental and applied. I discuss here the use of this well-established technique in two fundamental problems: **(1)** very-low frequency gravitational wave (GW) searches and **(2)** general relativistic redshift measurements.

(1) In the deep space GW observations, the Earth and distant spacecraft are free test masses with the ground Doppler tracking system measuring the Earth-spacecraft relative velocity [1, and references therein]. Spacecraft distances of several au make such a detector large compared to low frequency gravitational wavelengths.

The presence of a stochastic GW background can be detected using the two(three)-way Doppler frequency power cross-spectrum for a pair of spacecraft [2]. If the background is assumed isotropic, the cross-spectrum dependency on the angular separation between spacecraft can be factorized in two limits: when $2\pi fl \ll 1$ or $2\pi fl \gg 1$, where f is the GW frequency and l is the spacecraft distance (see Fig. 1). We are considering the low-frequency limit (with $f <\sim 10^{-7}$ Hz) since the expected power spectrum for the hypothetical GW background is larger in this limit and comparable to the error budget.

A model accounting for geometric, propagation, and instrumental effects is used to compute two(three)-way Doppler frequency predictions, which are subsequently subtracted from the observed time series. The residuals are used to compute cross-spectra that can be searched for the evidence of the stochastic background.

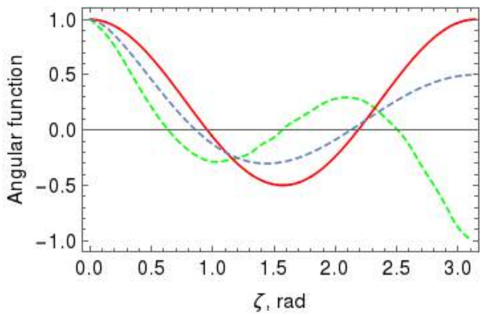


Figure 1: Angular dependencies for the cross-spectra in the presence of GW background. The solid red curve corresponds to the $2\pi fl \ll 1$ limit; the dashed green curve - the same for $2\pi fl \gg 1$; the dashed blue curve - the Hellings-Downs curve used in the pulsar timing studies, which is equivalent to the one-way Doppler case in the $2\pi fl \gg 1$ limit.

(2) A test of the gravitational redshift effect, is currently being conducted with Russian Federal Space Agency's RadioAstron spacecraft, which is on a highly eccentric orbit around Earth [3, and references therein]. In this experiment, the frequency change of RadioAstron's on-board H-maser due to a varying gravitational field is measured by comparing it with an H-maser at a ground station by means of X- and K-band (8.4 and 15 GHz, respectively) radio links. The observations performed and analyzed to date have already allowed to measure the effect with a relative accuracy of 4×10^{-4}. With additional observations scheduled for the summer of 2016, it is expected to reach 2.5×10^{-5}, an improvement of almost a magnitude over the 40-year old result of the Gravity Probe A mission.

References

[1] J. W. Armstrong. Low-Frequency Gravitational Wave Searches Using Spacecraft Doppler Tracking. *Living Reviews in Relativity*, 9, January 2006.

[2] T. K. Kalaydzhyan and D. A. Duev. in prep. 2016.

[3] D. A. Litvinov, U. Bach, N. Bartel, K. G. Belousov, M. Bietenholz, A. V. Biriukov, G. Cimo, D. A. Duev, L. I. Gurvits, A. V. Gusev, R. Haas, V. L. Kauts, B. Z. Kanevsky, A. V. Kovalenko, G. Kronschnabl, V. V. Kulagin, M. Lindqvist, G. Molera Calves, A. Neidhardt, C. Ploetz, S. V. Pogrebenko, N. K. Porayko, V. N. Rudenko, A. I. Smirnov, K. V. Sokolovsky, V. A. Stepanyants, J. Yang, and M. V. Zakhvatkin. RadioAstron gravitational redshift experiment: status update. *ArXiv e-prints*, May 2016.

Notes

The curious case of J1415+1320

Harish Vedantham

The OVRO 40 m dish has been monitoring about 2000 blazars at 15 GHz on a $\sim$ weekly cadence since 2008. Since blazars are bright compact radio sources, the dataset forms an excellent resource to study propagation effects such as lensing. Lensing is a result deflection and (de-)focussing of light rays, caused by spatial gradients and curvature in the refractive index of the propagation medium. In the well known case of gravitational lensing, the Shapiro delay provides an effective refractive index. Additionally, refraction in interstellar plasma structures can also lens radio sources. Plasma lensing has been used to explain Extreme Scattering Events (ESE)— symmetric 'U'-shaped events seen in some radio light-curves (Fiedler et al. 1987). The symmetry of such light-curves has motivated models involving refraction by spherical or filamentary plasma structures. The required column of electrons however imply extreme plasma densities— $n_{\rm e} \sim 10^3 - 10^4\,{\rm cm}^{-3}$ (Clegg et al. 1998), whereas the ambient ISM density is only $n_{\rm e} \sim 0.1\,{\rm cm}^{-3}$. This over-pressurization problem is avoided in 2 classes of models: (i) those involving self-gravitating sub-stellar objects which will have to comprise a significant fraction of Galactic dark matter to account for the observed events rates (Walker & Wardle, 1998), and (ii) a chance co-incidence of long sheets viewed edge-on (Pen & King, 2012) that can provide the required column with modest over-densities. Observations have not discriminated between the two model-sets, and ESEs have remain an unsolved mystery for over 3 decades.

We undertook a search for symmetric U-shaped features in the OVRO data archive. Though a handful of candidates were identified, J1415+1320 clearly stood out for 2 reasons. J1415+1320's light curve shows little intrinsic (random flares plus red-noise) variability around the distinct U-shaped events, and (ii) the U-shaped events seem to repeat about every 5 years, whereas the expected ESE rate is $\sim 10^{-3}\,{\rm yr}^{-1}$. Moreover, collating data from similar observational programs at other frequencies shows that the U-shaped events are largely achromatic in their extent and demagnification over a factor of ~ 20 in wavelength, whereas refractive index of plasma is expected to evolve as λ^2. J1415+1320 is likely not showing ESEs, which leaves us with the gravitational lensing hypothesis.

The radio source in J1415+1320 is co-incident (decentering of 13 mas or 50 pc) with the optical light centroid of an edge-on spiral galaxy at $z \approx 0.24$ (Perlman et al. 2002). There is debate as to whether the radio sources resides in the spiral or is a background object. For gravitational lensing to be viable, the latter must be true and to avoid macro-lensing by the spiral (which is not observed), the radio sources can be no further than 250 Mpc behind the spiral. Lens modeling yields the most likely mass-scale of lensing objects (which necessarily reside in the spiral) to be well in excess of 100 $M_\odot$! This unusual conclusion must await independent confirmation, especially since finding a radio source immaculately aligned with a foreground spiral is statistically unlikely.

J1415+1320 is not uniquely poised to show microlensing variability, and upcoming transient surveys must find many microlensing candidates (plasma or gravitational). The forgoing analysis of J1415+1320 was only possible due to the excellent time-cadence of the OVRO data (whence the identification of the U-symmetry), and availability of multifrequency data. Multiwavelength follow-up of future transient candidates with ~ 1 week cadence can unravel a rich class of radio microlensing events.

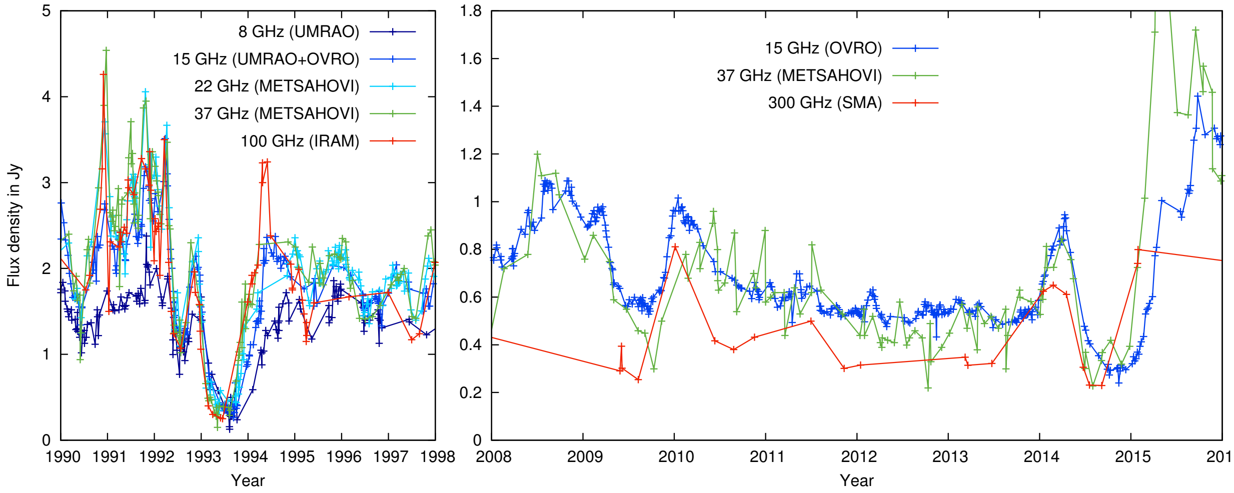


Figure 1: Mutlifrequency multi-decade light curve of J1415+1320 showing 3 remarkably symmetric and largely achromatic 'U'-shaped events. Data between 1998 and 2008 are available and shows a weaker event, but are not included here for brevity. Credit is due to the observatories (mentioned in the legend) for making their data available.

Notes

Single dish & VLBI in Japan

Kenta Fujisawa (Yamaguchi University, Japan)

1. VLBI

VERA[1] is a dedicated VLBI array in Japan that consist of four 20-m radio telescopes operated by National Astronomical Observatory of Japan (NAOJ).The baseline length of VERA ranges from 1000 to 2300 km, the observing frequencies are 6.7, 22, and 43 GHz. The prominent feature of VERA is “dual-beam” system designed for simultaneous observation of close pair of sources. The atmospheric fluctuation, an obstacle for VLBI observation, is cancelled out with this dual-beam so that high-precision astrometry can be made. Observing proposals for VERA are invited twice a year.

There are, like a famous radio telescope Nobeyama 45-m, more than ten telescopes in Japan. VERA, Usuda 64-m, Kashima 34-m, and some university telescopes are incorporated to the Japanese VLBI Network (JVN)[2]. JVN is operating at 6.7, 8, and 22 GHz. The longest baseline is 2500 km. JVN is not an open-use array, but researchers may use it under collaboration with JVN team.

2. Ibaraki and Yamaguchi Stations

Two stations of JVN, Ibaraki and Yamaguchi, have two telescopes at each site. These four telescopes were owned by a private company (KDDI) and used for satellite communication in the past.


Ibaraki (left: Takahagi, right: Hitachi)

Two telescopes at Ibaraki station (called Hitachi and Takahagi, upper panel) have 32-m diameter, 6 – 9 GHz cooled receiver, and 200 m baseline. They are used as two single-dishes for maser astronomy, or two-element interferometer. At Yamaguchi station, No.1 (32-m) and No.2 (34-m) telescopes are located on 110-m baseline (lower panel). No.1 has been used since 2002, and No.2 has just started test observations from April 2016. In May, the first fringe of Yamaguchi interferometer was obtained.


Yamaguchi (left: No.1, right: No.2)

Both Ibaraki and Yamaguchi interferometer would be operational within two years and have detection sensitivities of 1 mJy level for continuum source at 6 and 8 GHz bands. Although there is no advantage in the angular resolution, they have advantages of sensitivity, long observing time, and agility, because these telescopes are operated by Ibaraki University and Yamaguchi University respectively. The observation plan is determined by researchers of these universities. Sources with high variability, such as X-ray binary or transients, would be the main target of these interferometers. These two interferometers located 1000 km apart can be used for VLBI observation with high precision amplitude calibration.

References

[1] http://veraserver.mtk.nao.ac.jp/index.html
[2] http://www.astro.sci.yamaguchi-u.ac.jp/jvn/eng/index_e.html

Notes

Boutiques & Behemoths

The Ecosystem of Radio Observatories

Dale A. Frail, National Radio Astronomy Observatory

There is a Cambrian-like explosion currently underway in radio astronomy, with new and improved facilities at MHz and GHz frequencies, covering many ecological niches big and small. At MHz frequencies radio astronomy has returned to its early roots. Motivated by the study of the dark ages and the epoch of re-ionization, there are dipole arrays capable of imaging the full field of view, backed up by advanced calibration and imaging algorithms. At GHz frequencies new wide-field capabilities have been enabled by the construction of either large numbers of small diameter dishes, the installation of phased array feeds on single dishes and imaging interferometers, or substantial sensitivity upgrades to existing facilities. Virtually all of these observatories have the exploration of the time domain sky as one of their key science drivers.

I will start with a recap of the frontier science areas that have been identified at this conference as being ripe for new discovery. There are two fundamental ways to make transient discoveries. The first method is the careful, systematic exploration of the radio sky. This is generally the purview of wide-field instruments that undertake all-sky GHz surveys. The VLA Sky Survey (VLASS) at the JVLA and related surveys with ASKAP (VAST) and Apertif represent exciting new opportunities for time-domain science. Two of the frontier science opportunities in this regime include the much-neglected Galactic transients at both MHz and GHz radio frequencies and the long-duration MHz sky as studied by LOFAR, MWA, GMRT and LWA.

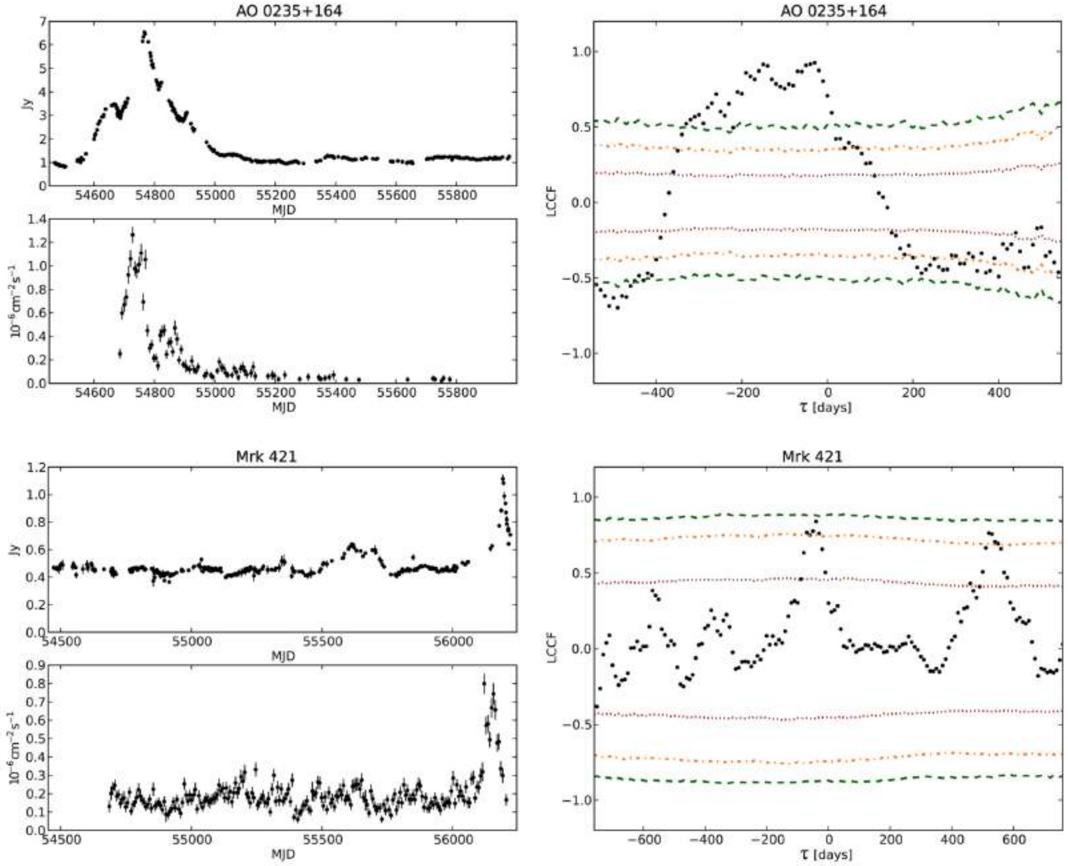
The second approach is through direct follow-up of interesting transients identified at other wavelengths or discovered from radio surveys directly. This is the domain of high forward gain, generally narrow field instruments, although there is an important role for smaller specialized instruments. Frontier science opportunities in this regime include fast radio bursts (FRBs), extreme scattering events (ESEs) and the electromagnetic counterparts to gravitational waves. I will show, based on past examples, that the optical transient sky is remarkably decoupled from the strange goings-on in the radio sky. However, there is a strong link between radio transients and high energy emission at X-rays and gamma-rays. At this meeting it is expected that we will explore the strong synergy between the VLASS and upcoming Spektr-RG Mission.

Notes

Radio – high-energy correlations in AGN variability

A. C. S. Readhead – Caltech

The OVRO 40 m Telescope is dedicated to a program, started in 2008, of monitoring ~1830 active galaxies and highly variable galactic radio sources at 15 GHz twice a week in support of Fermi-GST, NuSTAR, and the VHE experiments HESS, MAGIC and VERITAS. The primary scientific objective is to determine the location of the high-energy emission through studying the correlation between radio flux density variations and activity at X-ray and gamma-ray energies using rigorous statistical procedures developed in this program. The accompanying figure shows two examples of physically significant cross-correlations between activity at radio wavelengths and at gamma-ray energies. The physical significance of the level of cross-correlation, shown by the 1-sigma (dotted purple), 2-sigma (dot-dashed orange), and 3-sigma (dashed green) curves, has been calculated by modeling the variability in each source by fitting power-law spectra to the radio frequency and gamma-ray light curves and determining the uncertainties in the slopes of these curves. A large number of simulated light curves having random variations with the same spectra over the same range of spectral indices is then generated and these are cross-correlated to determine probability of these levels of cross-correlation being a result of random variations that are not related in the two energy bands. In this way the significance levels that the activities in the two energy ranges are physically correlated are calculated. A great strength of this approach is that as the observing period is extended the uncertainties in the slopes of the power law variations are reduced at both radio and X-ray energies, which improves the confidence levels more rapidly than sqrt(t). This study has shown that in cases where a statistically significant cross-correlation is observed the gamma-ray variations precede the 15 GHz radio variations by a few tens to a few hundred days in the observer frame. This is important for theories about the origin of the gamma-ray emission, some of which place the gamma-ray emission site in the radio emission regions, and is being modeled with simulations by a number of theorists.



Two examples of significantly correlated variability in the radio and gamma-ray bands. The figures on the left show the radio (top – from the 40 m telescope at OVRO) and gamma-ray (bottom – Fermi) lightcurves for the blazars AO 0235+164 and Mrk 421. The figures on the right show the correlation coefficients at different epochs between the bands; the colored lines indicate different significance levels.

Lunch discussions

1. Instrumentation (Sandy Weinreb)
2. EM strategies in the GW era (Mansi Kasliwal, Gregg Hallinan)
3. Phased arrays (Jim Cordes)
4. After SDSS-4 (Juna Kollmeier)

V. Radhakrishnan, Frank Kerr and Gordon Stanley at Red Rock Canyon, en route to OVRO in December 1960 soon after Stanley took over as observatory director, and during their days as members of M. I. B.

Lunch Discussions of Instrumentation

Sander Weinreb, sweinreb@caltech.edu

Friday, July 22, 2016, 1215-1400 and Saturday, July 23, 2016, 1300-

I will lead a discussion given the title “RF/CASPER”. This could be interpreted as RF components which are well developed, documented, and can be easily implemented as are the CASPER digital components. However we can also discuss CASPER, in advance or in more detail to the talk on this topic that Dan Werthimer will be giving later in the day.

The instrumentation discussion can be split into two topics:

Instrumentation Infrastructure for Large Meter and Decameter Arrays

The cost of radio astronomy instrumentation in the range up to 1 GHz has greatly declined due to lower cost components. This is especially true when wide field of view is desired with arrays of small telescopes or multiple feeds on a large structure are considered. As an example, 5m paraboloids on fixed mounts can be purchased for <$2K, and low cost 14m paraboloids are being implemented for the UCB HERA project. Low cost feeds and LNA’s have been developed by the amateur radio community. Aluminum rod/wire antennas and feeds fashioned from aluminum tubing can be inexpensively constructed. Uncooled LNA’s with ~20K noise for 1.4 GHz are available for <$200 and a 0.3 to 1.1 GHz LNA with ~10K noise temperature has recently been developed by Schleeh for the SKA. Some useful web sites for amateur radio equipment are: http://www.radioastronomysupplies.com/, www.qrz.com, and http://rfdesignuk.com/products.htm.

For the fiber optic infrastructure low cost laser transmitters and receivers for the 10 to 2500 MHz range have been recently developed at Caltech. The most important parameters of the link are: Gain, 0 +/-2 dB, Noise Figure <12 dB, and P1db -10dBm. The noise figure thus requires about 30 dB gain between the antenna and link and the RFI level must then be <-10 dBm at the link input. The component cost of a link is under $50. A report on the link it available by contacting sweinreb@caltech.edu.

Receivers for the Next Generation VLA, ngVLA.

NRAO is leading studies of a next generation of the VLA. It is generally considered to be an array covering the frequency gap between SKA and ALMA and with order-of-magnitude greater sensitivity and resolution than the VLA. Of the order of 256 dishes with 18m diameter on a 300km baseline are being considered. Cost of implementation and operating cost are major factors. A prototype of the dish is needed to give creditability to a cost estimate. A receiver concept covering 1.2 to 116 GHz with four feeds in one cryogenic package is being considered and will be presented at the forthcoming Kavli 2 meeting in Baltimore on August 4, 2016. Key parameters are the sensitivity, Ae/Tsys, of receiver and the thermal design for low maintenance cost. Frequency ranges as large as 6:1 for each receiver have been made feasible by the development of quad-ridge flared horn (QRFH) feeds and very wideband integrated circuit low noise amplifiers.

A first prototype of a 1.2 to 116 GHz receiver package is planned for implementation at Caltech in the next 2 years with telescope tests by late 2018. This type of versatile receiver with very wide frequency coverage may have application to other existing or planned telescopes for new astronomy topics that are being discussed at this symposium. Many telescope in the 12m size range with simultaneous operation in the 2.3 to 14 GHz range are being implemented following the VLBI2010 recommendations.

Participants are invited to bring up other instrumentation needs for new astronomy experiments.

Advanced L-Band Phased Array Camera for Arecibo (ALPACA)

B. Jeffs & K. Warnick (BYU), G. Cortes-Medellin (U. Antioquia, Colombia)
D. Campbell, S. Parshley & J.M. Cordes (Cornell), R. Minchin (USRA Arecibo), July 13, 2016

Scientific Drivers: Primary drivers include topics in extreme gravity, gravitational waves, extragalactic bursts of unknown origin, mini halos in ΛCDM cosmology, and the search for extraterrestrial intelligence (SETI). Major surveys in these areas can be conducted commensally. All benefit from the unique combination of wide field of view and high sensi.tivity that Arecibo will provide with ALPACA. Specific surveys are driven by the following key science:

1. *Extreme Gravity and Fundamental Physics:* NS-NS binaries, NS-BH binaries, precision mass determinations, tests of GR, nanohertz gravitational wave detection.
2. *Radio transients:* Unidentified millisecond bursts of extragalactic origin, rotating radio transients, intermittent pulsars, giant-pulses.
3. *Near-field HI 21 cm line cosmology;* discover the HI population at lowest masses; establish the imprint of the cosmic web on galaxy evolution; and measure the mass density along Coma-A1367 and Pisces-Perseus filaments.
4. *The Search for Extraterrestrial Intelligence:* SETI searches can operate very effectively as commensal projects, covering much of the sky several times while operating alongside survey observations for other science areas.

Figure 1 [left] shows two metrics for comparing ALPACA with other telescopes: survey speed (abscissa) plotted against detection distance (or "reach", ordinate). ALPACA gives a large survey speed surpassed significantly only by CHIME. However, Arecibo's reach (via ALFA or ALPACA) is far larger than CHIME's and other high survey-speed telescopes, including APERTIF, ASKAP, and MeerKAT. Reach is important for fast radio bursts (FRBs; e.g. center panel) that are now known to originate from extraga lactic sources but at as yet uncertain distances. The right-hand panel shows the beam patterns for ALPACA and the ALFA system that it will replace.

Instrument Description: ALPACA's principal operational specifications are presented in the following table:

Dual polarization beams	40 beams, spaced 2 arcmin, close to Nyquist spacing, steerable in FOV
Rotator	±15 deg specification
System temperature	specification < 35 K, goal < 30 K
Frequency range	1280 MHz to 1720 MHz (determined by RFI issues)
Input BW to beamformer	312.5 MHz (selectable within the 440 MHz band)
Coarse channels per polarization	800 channels, 391 kHz BW per chan (dictated by fast burst searches)
Fine individual channel BW	12.2 kHz for HI in external galaxies
Fine channel overall bandwidth	150 MHz max, scalable for finer channel bandwidths of 12.2 kHz
Sample rate (coarse, & fine spectrometer)	64 usec (for pulsars and FRBs), > 0.1 sec (for spectroscopy)
Digital back end architecture	Hybrid FPGA polyphase filter bank and GPU correlator / beamformer

The overall architecture design of the ALPACA system is shown in Fig. 2 [Left]. There are 160 signal streams (from 80 dual-polarization dipoles) at the output of the camera. Some key system features include:

1. *Fully Cryogenically Cooled:* ALPACA's novel design is the first fully cooled (both LNAs and antenna elements) L–band PAF, as seen in Figures 2 [Right] and 3 [Left]. The dewar includes a radio-transparent but strong HDPE foam dome to give dipoles an unobstructed view and to handle the stresses of the dewar vacuum. This is internally supported by Rohacell foam, which is also transparent at L-band. This eliminates the problematical large unsupported vacuum window.
2. *Array Geometry:* The dipoles are distributed on a 4-fold symmetric square grid (Fig. 3, *Center*) inside a 122 cm diameter circle, allowing full sampling of the entire available FoV of the Arecibo telescope at L-band.
3. *Proven Element and Array Design:* Figure 3 [Center] and [Right] show the actual 19 dual-pol element array which was successfully tested on the Arecibo Telescope to demonstrate the design concepts. ALPACA will have more than four times the number of elements. The easily serviced modular removable element in Figure 3 [Right]: uses a numerically optimized modified sleeve dipole design with thickened arms for wideband operation, excellent impedance matching, and favorable radiation pattern. The input match is better than -12 dB at the target band of operation from 1.28 GHz to 1.72 GHz.
4. *Real-time Correlator:* The digital back end is based on a full–array, full–time correlator to compute short term integrated array covariance matrices. This first-of-its-kind PAF processor architecture enables both post correlation beamforming (PCB) and real–time adaptive null forming RFI mitigation. With PCB, the integrated covariance matrices are stored so beamformed spectrometer outputs can be computed after the fact, with as many beam look directions as desired. New beamformer weights and pattern shapes can be applied to improve detection performance without having to re-run the observation. Also, real–time array processing to cancel moving RFI requires this real–time correlator architecture.
5. *Commensal Transient Search and HI Studies:* In addition to the correlator outputs for PCB, the back end computes, concurrently, a seven-beam real–time beamforming spectrometer data set. This fast-dump integrator is optimized for oportunistic transient detection and will operate at all times, regardless of what the PCB observation target is.

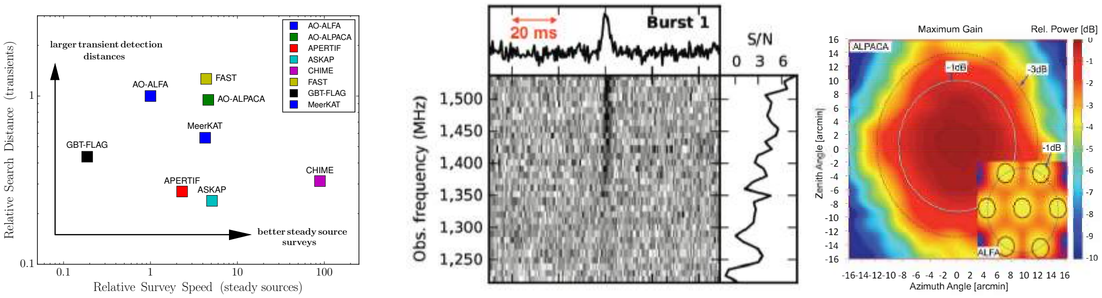


Figure 1: [Left]: Characterization of ALPACA and other telescope/receiver combinations using the standard survey speed appropriate for steady sources (x axis) and search distance or reach of a given telescope (y axis) which is important for surveys for transients, such as fast radio bursts (FRBs), intermittent pulsars, and ETI sources. All are L-band ($\sim$ 1.5 GHz) systems except for CHIME, which operates from 0.4 to 0.8 GHz and is a transit instrument. [Center]: Frequency-time plot for FRB121102 discovered at Arecibo in the PALFA survey (Spitler et al. 2014). Showing the averaged time series in the top panel and the spectrum in the right subpanel. Subsequent redetections show that the spectral shape is highly dynamical. [Right]: Gain vs. azimuth and zenith angles for ALPACA, showing its footprint in comparison with ALFA.

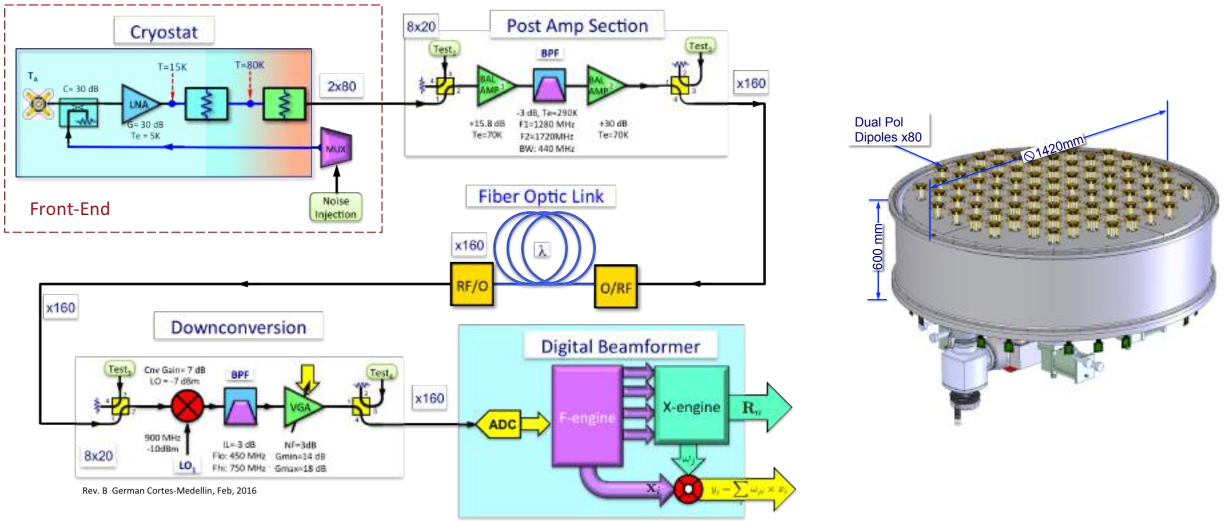


Figure 2: [Left]: Overall architecture of the proposed ALPACA instrument. [Right]: The proposed ALPACA 80 dual-pol element PAF array over the 142 cm diameter ground plane, with HDPE top-hat cryo dome removed.

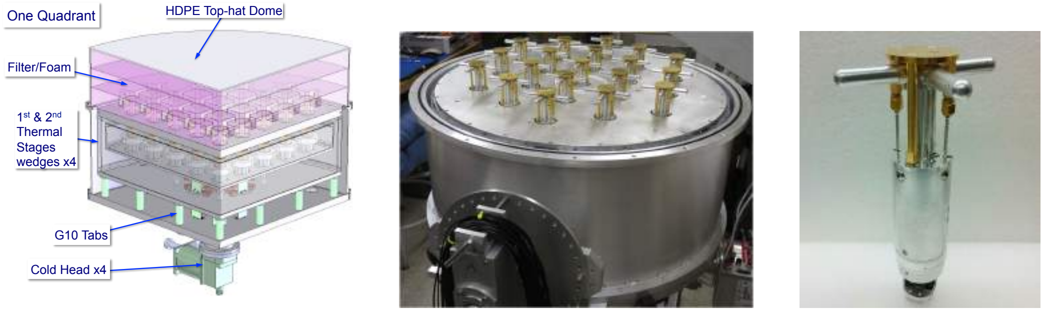


Figure 3: [Left]: Cutaway schematic of ALPACA cryostat showing inner structure of the top-hat dome and Rohacell foam layers. [Center]: Successfully tested (at Areciobo) AO-19 cryo-PAF without three foam layers and HDPE top-hat dome. [Right]: Dipole/LNA re-insertable package, each cylinder contains two LNAs. The press fit connectors are at its base.

Juna A. Kollmeier

AS4

With the detection of gravitational radiation, astrophysics has left behind mere “Multi-Wavelength” astronomy and has entered securely into the thicket of “Multi-Messenger Astronomy”. As a species, we have reached the computational capacity to *simultaneously* analyze the energetics and dynamics for any object class within the observable universe. It is an exciting, but complex time to be an astronomer. On the one hand, we are finding new phenomena through our augmented sensory capability (e.g. FRBs), but on the other we remain limited by resources and, more significantly, comprehensive theoretical understanding. O/IR spectroscopy remains an important component of that understanding for the foreseeable future. It is thus important to think about how we can make optimal use of our O/IR telescopes and spectrographs in the coming decades as we attempt to integrate the “multiple messengers” from a variety of astrophysical sources old and new.

The AS4 Steering Committee is currently thinking about how and whether the great success of the Sloan Digital Sky Survey can be extended into the 2020s. The current SDSS-IV program make use of the following hardware to do cosmology, galaxy structure and evolution, stellar astrophysics, and Galactic archaeology : a wide-field (7 deg^2 at Apache Point Observatory and 3.5 deg^2 at Las Campanas Observatory) high-resolution (R~22,500) multi-object (300 fibers) infrared (1.51-1.70 μm) spectrograph (APOGEE-N and APOGEE-S), two moderate (R~2000) resolution multi-object (1000 fibers) optical (.360-1 μm) spectrographs (the BOSS spectrographs) and an IFU mode in which a BOSS spectrograph is fed by fiber bundles (ranging in size from 19 to 127 fibers each) as opposed to the 1000 individual fibers.

Science relevant to this meeting that will not be done in SDSS-IV but that could be done in the future with modest changes to the instrumental setup include:

1) Fully mapping the Milky Way’s disk spectroscopically in the infrared.
2) Determining the multiplicity function for a wide range of masses and mass-ratios
3) Generating a comprehensive 3D Dust Map of the Milky Way
4) Mapping the accretion physics and mass growth around supermassive black holes
5) Understanding young stellar objects
6) Synergies with photometric surveys in the time domain (ZTF, LSST, TESS, Plato, K2)

Some examples of possible hardware upgrades, ranging from the modest to the very ambitious in scale include:

1) A rapidly (2 minute!) reconfigurable robotic fiber positioner
2) A wide-field IR Imager
3) A highly multiplexed IR spectrograph
4) A Flexible IFU that can be fed by a range of telescope apertures

Even though B&E 2016 rightly focuses on the exciting developments in Radio Astronomy, I will take the opportunity at the B&E meeting to engage the assembled community on the topic of “Multi-Messenger Astrophysics” and their thoughts on the brightest possible future for O/IR spectroscopic time-domain mapping of the Heavens.

A small snapshot of some of the students to have passed through OVRO. Left: Barry Clark circa 1960. Top right: Seth Shostak circa 1970. Bottom right: Myriad students during a a recent antenna construction expedition for the Owens Valley Long Wavelength Array.

Paricipants

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