Course II:
Compact Objects, the Dynamic Radio Sky, and 21st Century Radio Telescope Facilities

Jim Cordes
Cornell University

Five Lectures:

1. Astrophysics of neutron stars and other compact objects
2. Plasma propagation effects (ISM, IGM, ionosphere)
3. Astrometry of compact objects
4. **The dynamic radio sky (transients and variability)**
5. New radio telescope arrays for key science and discovery

Cornell University

Course II Lecture 4

The Dynamic Radio Sky* (Transients and Variability)

*Heraclitus: you don't see the same universe twice

- Radio transient phase space
- Plasma propagation effects
  - IGM, ISM
- Key Source Classes and Targets:
  - Prompt GRBs and
  - Orphan afterglows
  - Intermittent pulsars
  - Galactic center transients
  - Exploration of phase space
  - (aka fishing expedition)
- Commensal, synoptic surveys
- Multi-λ and multi-messenger synergies
  - cross triggering
    - e.g. NS glitch events for GW searches
  - joint statistics (radio-IR, etc)

- Exotica
  - Evaporating BHs
  - ETI technomarkers
  - particle events
  - etc

Radio Transients and the SKA as a Synoptic Survey Facility

Transients = discovery frontier for multi-λ EM + CR + GWs

- Less so at high energies
  - BATSE, RXTE/ASM, Beppo/Sax, SWIFT, GLAST, etc.
- More so for optical, radio

Fermi: full-sky survey every three hours for 1+ years

Optical: PanSTARRS, LSST, minutes to years

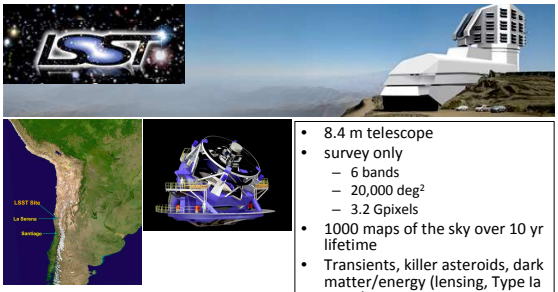
Points:

- Ways of looking at transient parameter space
- Rich variety of known transients: astrophysically important
- Tantalizing prospects for new kinds of transients
- Achieving a completeness level ~ γ/X-ray all-sky surveys

Radio Synoptic Survey Telescopes

- Early SKA science: now!

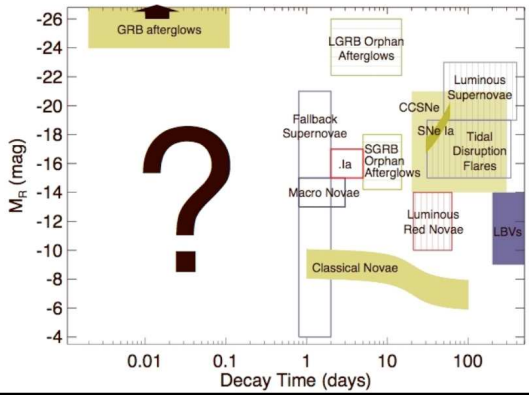
LSST = Large Synoptic Survey Telescope



- 8.4 m telescope
- survey only
  - 6 bands
  - 20,000 deg²
  - 3.2 Gpixels
- 1000 maps of the sky over 10 yr lifetime
- Transients, killer asteroids, dark matter/energy (lensing, Type Ia SNAe)

Transient Phase Space for LSST

From LSST Science Case Chapter on Transients & Variable Stars



Radio Transients are Prime for Exploration

No comprehensive survey of large phase space

- Need large AΩT (area, solid angle and time coverage)
- ns to years
- complex structures in the frequency-time plane ⇒ HPC processing

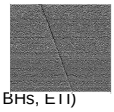
Nature can produce cheap radio photons via coherent radiation processes (N^2 vs N) so detectable to great distances

Fast transients are linked to extreme matter states ($\Delta t < 1$s)

… or ETI

Counterparts to known source classes

- Prompt radio bursts from GRBs
- Gamma-ray quiet, radio-loud GRBs



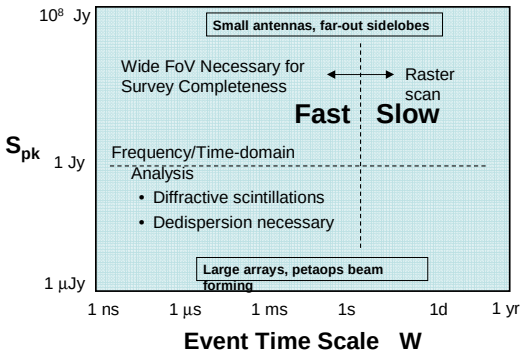
Expect new source classes (particle events, evaporating BHs, ETI)

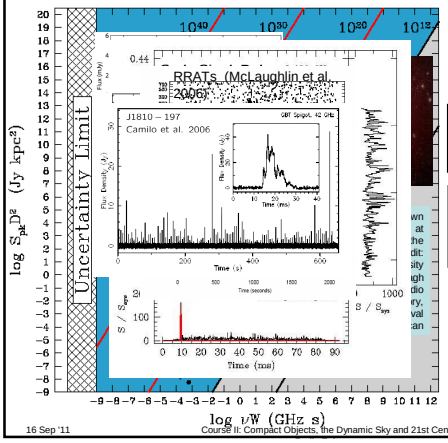
Beacons for probing the cosmic web and fundamental constants

- Intervening plasmas (IPM, ISM, IGM) ⇒ dispersion, scattering, scintillation
- Photon mass, charge from measured dispersion law (de Broglie 1940)

$$\Delta t = (e/8\pi^2)Dm_\gamma^2(\nu_2^{-2}-\nu_1^{-2}) + \text{plasma contribution}$$

Fast and Slow Transients





Phase subspace for transients:

$S_{pk}D^2$ vs. νW

$$kT_b = \frac{2S_{pk}D^2}{(\nu W)^2}$$

W = pulse width or characteristic time scale

Bower et al. 2007

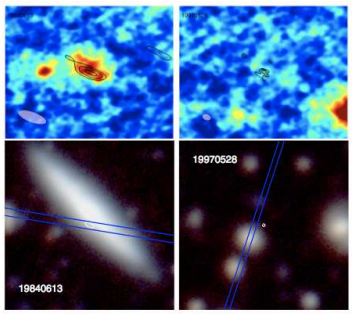
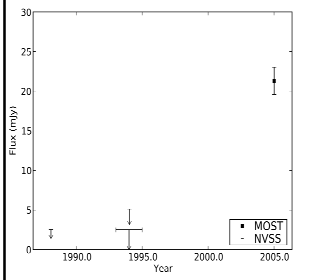
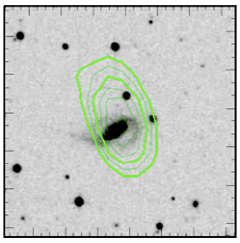


Figure 7: Deep radio (*top*) and optical (*bottom*) images associated with two radio transients (Bower et al. 2007). RT 19840613 is coincident with radio and optical emission while RT 19970528 has no counterpart in either band. In the radio images, the contours show the transient while the colors are the deep follow-up image. In the optical images, the white circle indicates the uncertainty in the position of the transient source.

Unknown transient: J060938-333508

K. Bannister et al. (2010)

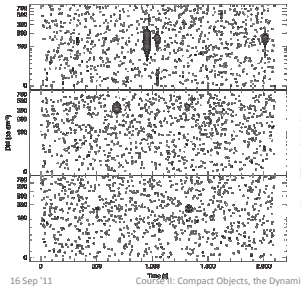




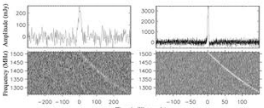
Rotating Radio Transients (RRATs)

Transient radio bursts from rotating neutron stars

M. A. McLaughlin[1], A. G. Lyne[1], D. R. Lorimer[1], M. Kramer[1], A. J. Faulkner[1], R. N. Manchester[2], J. M. Cordes[3], F. Camilo[4], A. Possenti[5], I. H. Stairs[6], G. Hobbs[2], N. D'Amico[5,7], M. Burgay[5] & J. T. O'Brien[1]



- RRATs appear to be highly modulated/spora dic pulsars



Arecibo transient object

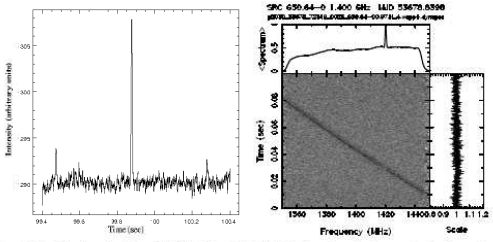
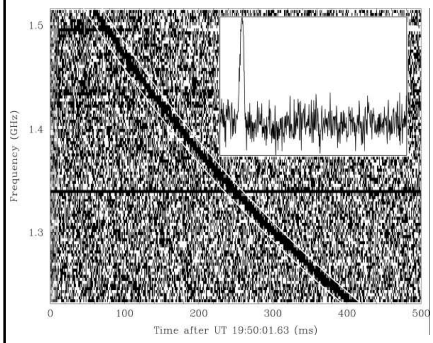


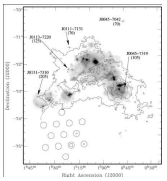
Fig. 3.— Right: Single pulse from PALFA object G50.64-00.97 showing the characteristic dispersion sweep $\Delta t \propto \nu^{-2}$DM where the dispersion measure DM is the column density of free electrons to the pulsar. The line in the top spectrum is 21 cm hydrogen. Left: Single pulses from PALFA object J1928+15. These consecutive, dedispersed pulses are the only three detected in a total of 1.2 hr. It appears to be a rotating radio transient (RRAT) with a period of 0.40 sec.

A Bright Millisecond Radio Burst of Extragalactic Origin

D. R. Lorimer,[1,2]* M. Bailes,[3] M. A. McLaughlin,[1,2] D. J. Narkevic,[1] F. Crawford[4]

Science Express
27 Sep 2007





W ~ 4.6 ms (ν / 1.4 GHz)$^{-4.8\pm0.4}$

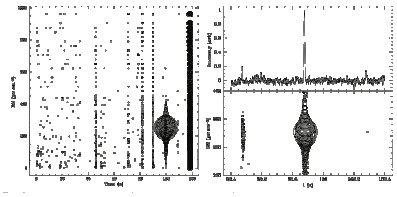
DM ~ 375 pc cm^{-3}

Steep spectrum (α=-4)

Fast Transients in PALFA Arecibo Survey

ARECIBO PULSAR SURVEY USING ALFA: PROBING RADIO PULSAR INTERMITTENCY AND TRANSIENTS

J. S. Deneva[1], J. M. Cordes[1], M. A. McLaughlin[2], D. J. Nice[3], D. R. Lorimer[2], F. Crawford[4], N. D. R. Bhat[5], F. Camilo[6], D. J. Champion[7], P. C. C. Freire[8,2], S. Hotz[1], V. I. Kondratiev[9], J. W. T. Hessels[9,10], F. A. Jenet[11], L. Kasian[12], V. M. Kaspi[12], M. Kramer[13,10], P. Lazarus[12], S. M. Ransom[14], I. H. Stairs[15,5], B. W. Stappers[16], J. van Leeuwen[10,11], A. Brazier[1], A. Venkataraman[9], J. A. Zellwitz[10], and S. Hogendorp[1,3]



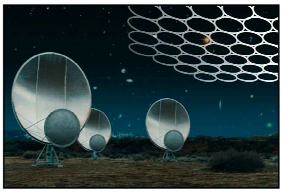
- A series of 3 dispersed pulses separated by 0.4 sec
- No repeats in any other observations

Limits on Pulses of Arbitrary Origin

- Lorimer et al. detection (if cosmological) implies that many more events should already have been detected (Parkes and Arecibo) ~ 1000
- Caveats: RFI, pulse broadening in the IGM for sources of weak events beyond nominal 0.5 Gpc of L event.
- Limits from PALFA data can be placed on weak to strong events that enter the telescope optics from the sky directly
- Limits on very strong events result from consideration of scattering into the optical path
- On axis gain:,
  - $G_{max} = 4\pi A_e/\lambda^2$ $\Omega = \lambda^2/A_e$ constrain frequent, weak events
- Off axis (far-out sidelobes):
  - G ~ 1 $\Omega \sim 2\pi$ constrain rare v. strong events

Fly's Eye Surveys

- Point N antennas in N separate directions
- → total instantaneous solid angle coverage
  - $\Omega_{total} = N\Omega_i \approx N\lambda/D \approx N$ deg^2 for 12 m antennas at 1 GHz



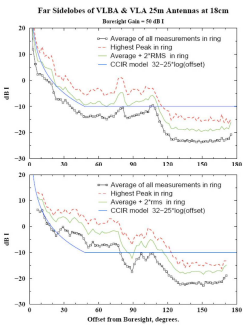
No detection of any events like the Lorimer pulse

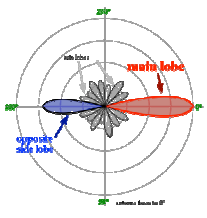
Inconsistent with Lorimer pulse originating from a cosmological source

Conclusion: Lorimer burst not astrophysical

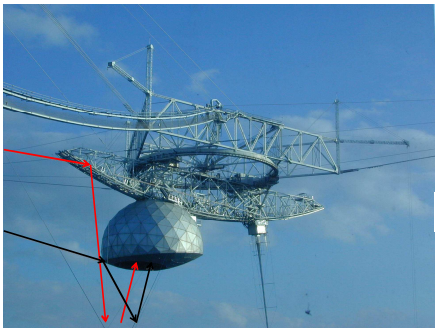
Burke-Spolaor t al. : similar bursts may be atmospheric in origin

All Antennas are "Full Sky" Telescopes





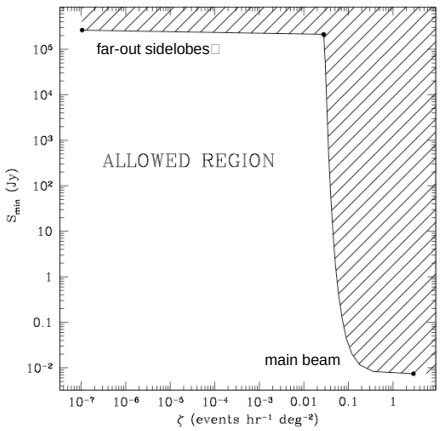
Multipath into Arecibo's Optics



Multipath yields constructive /destructive interference across the ALFA focal plane

$$A(\mathbf{x}') = \sum_j a_j e^{i\phi_j(\mathbf{x}')}$$

PLD ~ λ ~ 20cm



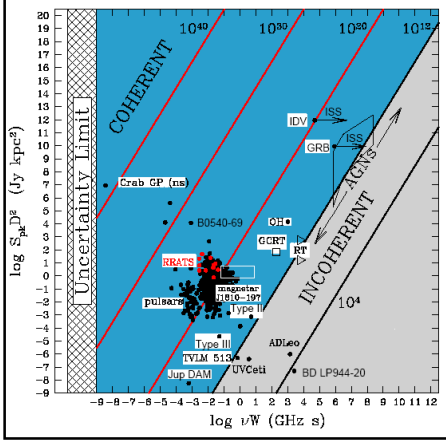
LONG DURATION RADIO TRANSIENTS LACKING OPTICAL COUNTERPARTS ARE POSSIBLY GALACTIC NEUTRON STARS

E. O. Ofek[1,2], B. Breslauer[3,4], A. Gal-Yam[1], D. Frail[4], M. M. Kasliwal[1], S. R. Kulkarni[1] & E. Waxman[3]

Draft of October 19, 2009

ABSTRACT

Recently, a new class of radio transients in the 5-GHz band and with durations of the order of hours to days, lacking any visible-light counterparts, was detected by Bower and collaborators. We present new deep near-Infrared (IR) observations of the field containing these transients, and find no counterparts down to a limiting magnitude of $K = 20.4$ mag. We argue that the bright (> 1 Jy) radio transients recently reported by Kida et al. are consistent with being additional examples of the Bower et al. transients. We refer to these groups of events as "long-duration radio transients". The main characteristics of this population are: time scales longer than 30 minute but shorter than several days; very large rate, $\sim 10^3\,\mathrm{deg}^{-2}\,\mathrm{yr}^{-1}$; progenitors sky surface density of $> 60\,\mathrm{deg}^{-2}$ (at 95% confidence) at Galactic latitude $\sim 40°$; 1.4–5 GHz spectral slopes, $f_\nu \propto \nu^\alpha$, with $\alpha \gtrsim 0$; and most notably the lack of any X-ray, visible-light, near-IR, and radio counterparts in quiescence. We discuss putative known astrophysical objects that may be related to these transients and rule out an association with many types of objects including supernovae, gamma-ray bursts, quasars, pulsars, and M-dwarf flare stars. Galactic brown-dwarfs or some sort of exotic explosions in the intergalactic medium remain plausible (though speculative) options. We argue that an attractive progenitor candidate for these radio transients is the class of Galactic isolated old neutron stars (NS). We confront this hypothesis with Monte-Carlo simulations of the space distribution of old NSs, and find satisfactory agreement for the large areal density. Furthermore, the lack of quiescent counterparts is explained quite naturally. In this framework we find: the mean distance to events in the Bower et al. sample is of order kpc; the typical distance to the Kida et al. transients are constrained to be between 30 pc and 900 pc (at the 95% confidence level); these events should repeat with a time scale of order several months; and sub-mJy level bursts should exhibit Galactic latitude dependence. We discuss two possible mechanisms giving rise to the observed radio emission: incoherent synchrotron emission and coherent emission. We speculate that if the latter is correct, the long duration radio transients are sputtering ancient pulsars or magnetars and will exhibit pulsed emission.



Phase Space for Transients:

$S_{pk}D^2$ vs. νW

$$kT_b = \frac{2S_{\rm pk}D^2}{(\nu W)^2}$$

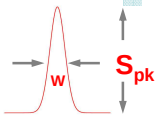
W = pulse width or characteristic time scale

Maximal Amplitudes of Giant Pulses

$$L_r = \epsilon_r \dot{E} = \epsilon_r I \Omega \dot{\Omega}$$

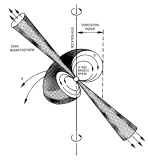
$$\epsilon_r \approx \left(\frac{\Omega_r}{4\pi}\right) 10^{-1.7} \quad \text{Crab}$$

$$S_{\rm peak} D^2 \approx 10^8\ \mathrm{Jy\,kpc^2} \frac{\epsilon_r \dot{E}_{38}}{\Delta\nu_{\rm GHz}} \left(\frac{4\pi}{\Omega_r}\right)$$



$$\dot{E} \approx 10^6 \times \dot{E}_{\rm Crab} P_{\rm ms}^{-4}$$

- High-field millisecond pulsars
- Reactivation of magnetospheres in merging NS-NS binaries (short GRBs, chirped GW sources)
- Extragalactic objects ➔ dispersion measure (DM)



Prompt Radio Bursts from γ-ray Bursts

Scale from γ-ray fluence:

$$L_r = \epsilon L_\gamma = \epsilon_r \left(\frac{E_\gamma}{\Delta t_\gamma}\right) \sim 10^{43} \quad 10^{46} \epsilon_{-5}\ \mathrm{erg\ s^{-1}}$$

Implied flux density:

$$S_{\rm pk} = \frac{L_r}{\Omega_r D^2 \Delta\nu_r} \sim 10^3\ \mathrm{Jy\ for\ D = 3\ Gpc}$$

Reasonable?

Compare with maximal pulsar energy losses

$$\dot{E} = I\Omega\dot{\Omega} \sim 10^{46.2}\ \mathrm{erg\ s^{-1}} \left(\frac{B}{100 B_{\rm Crab}}\right)^2 \left(\frac{0.1 P_{\rm Crab}}{P}\right)^{n+1}$$

n+1 ~ 3.5

Can radiation get out? (Macquart 2007)

Induced Compton and Raman scattering

Long bursts: hypernovae

⇒ dense plasma from pre-SN stellar wind, immersed in SF region

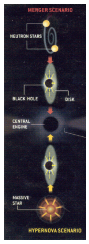
⇒ perhaps no emergent radio emission

mitigating effect: radio coherent, upboosted photons incoherent

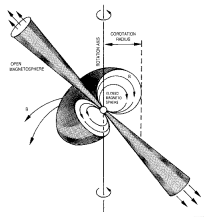
Short bursts: merging NS-NS, NS-BH

⇒ vacua that high-brightness radiation can get through

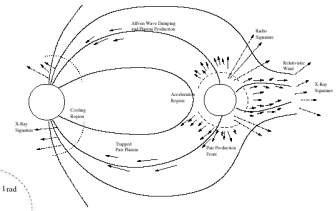
⇒ plausible radio bursts through reactivation of magnetosphere



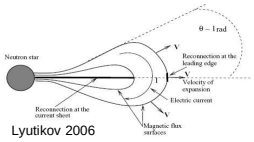
Isolated pulsar



Re-activation of pulsar action in mergers?

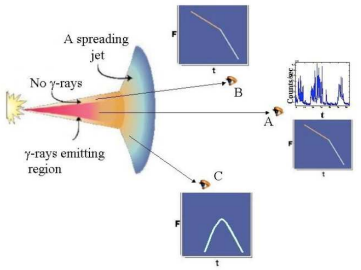


Hansen & Lyutikov 2000



Lyutikov 2006

Three Kinds of Bursts from Central Engines

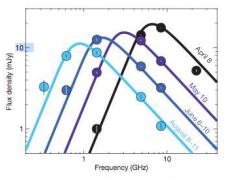


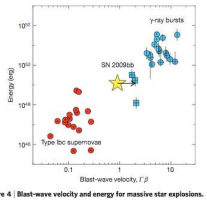
- On axis GRB + afterglow
- Orphan on-axis afterglow
- Orphan off-axis afterglow
- Beaming fractions for each type
- Orphan bursts vastly outnumber GRBs

Orphan Afterglows

A relativistic type Ibc supernova without a detected γ-ray burst

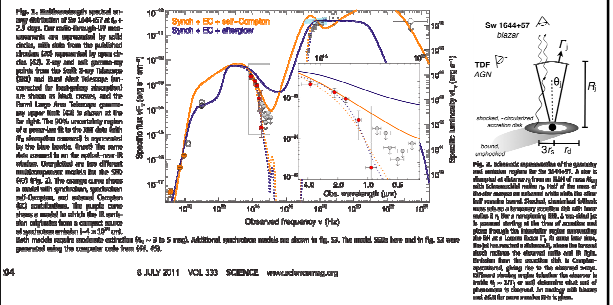
A. M. Soderberg[1], S. Chakraborti[2], G. Pignata[3], R. A. Chevalier[4], P. Chandra[5], A. Ray[2], M. H. Wieringa[6], A. Copete[1], V. Chaplin[7], V. Connaughton[7], S. D. Barthelmy[8], M. F. Bietenholz[9,10], N. Chugai[11], M. D. Stritzinger[12,13], M. Hamuy[3], C. Fransson[14], O. Fox[4], E. M. Levesque[1,15], J. E. Grindlay[1], P. Challis[1], R. J. Foley[1], R. P. Kirshner[1], P. A. Milne[16] & M. A. P. Torres[1]

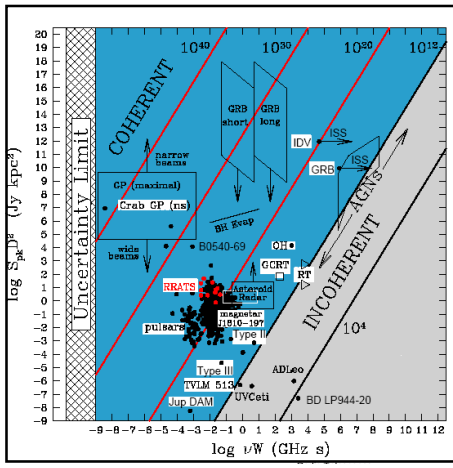




Tidal Disruption Events from Black Holes

Bloom et al. 2011





Filling phase space with hypothetical new discoveries:

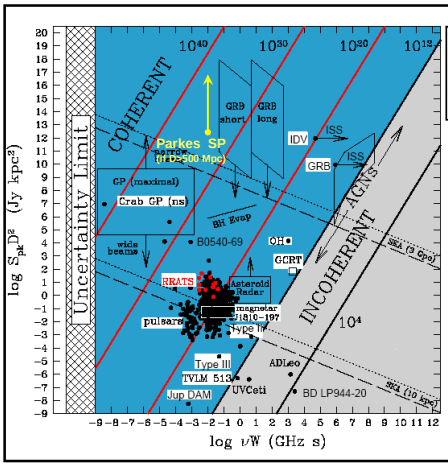
Prompt Gamma-ray emission

Evaporating black holes

Maximal giant pulse emission from pulsars

ETI's asteriod radar

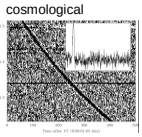
What else?



Detection limits for the SKA:

$S_{pk}D^2$ >threshold

⇐ Prompt GRBs and GRB afterglows easily seen to cosmological

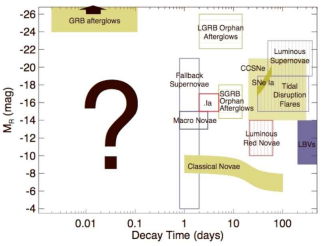


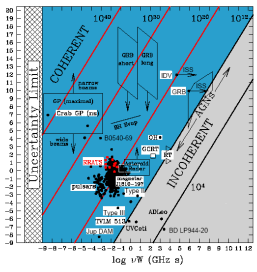
Giant pulses detectable to Virgo cluster

Radio magnetars detectable to Virgo

ET radar across Galaxy

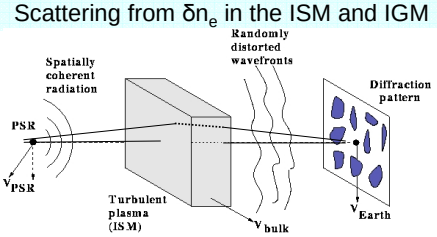
Optical and Radio Phase Spaces





The Medium is Sometimes the Message

Scattering from δn_e in the ISM and IGM

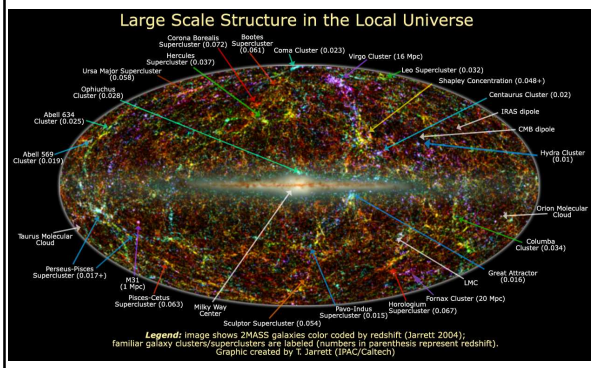


Electron density irregularities exist on scales from ~100s km to Galactic scales with a Kolmogorov-like wavenumber spectrum

$$\begin{aligned} \phi_d &= -\lambda r_e \int_{LOS} ds\, n_e(s) \\ n_e &= \overline{n}_e + \delta n_e \\ \Delta t_{DM} &= \frac{\phi_d}{2\pi\nu} \propto \frac{DM}{\nu^2} \end{aligned}$$

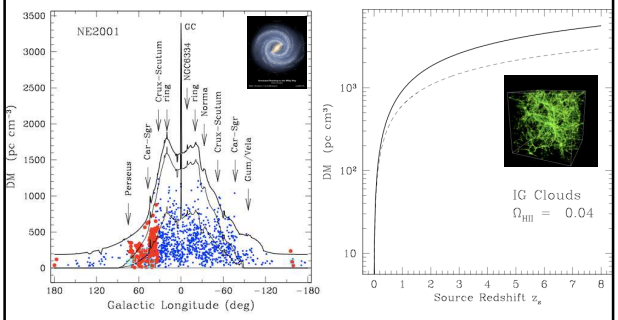
$$DM = \int_0^D ds\, n_e(s)$$

Large Scale Structure in the Local Universe

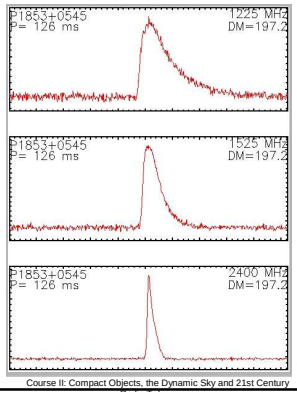


Dispersion Measures

ISM (b=0) IGM

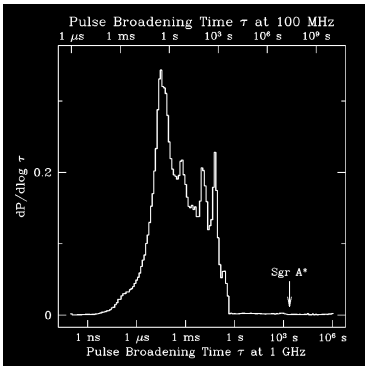


Pulse Broadening from Interstellar Scattering



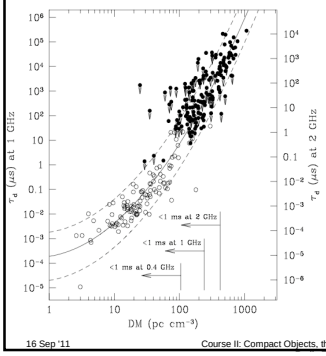
What Broadening Times to Expect?

Distribution of scattering times from Galactic sources calculated using NE2001 electron density model



Pulse Broadening Horizon

τ_d vs. DM for the ISM



How far can we look for pulses of a width W?

Need W ≥ τ_d (or lose sensitivity)

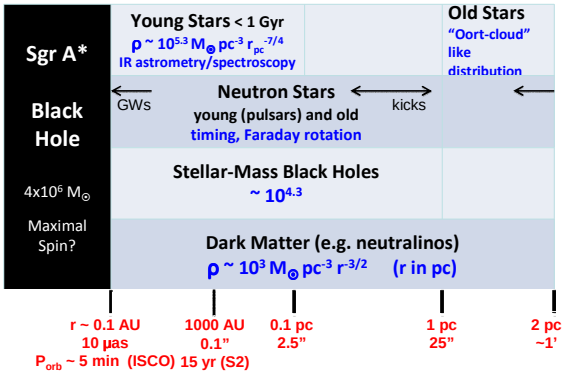
Galactic Horizon

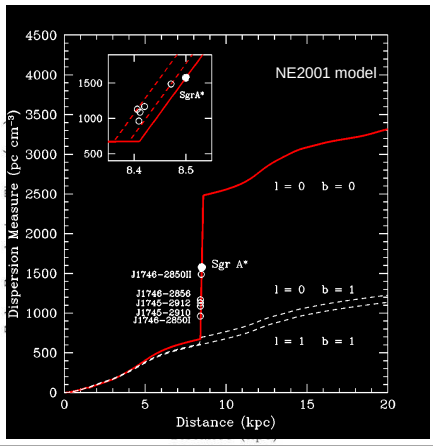
- 1 ms at 1 GHz to 5 kpc
- 1 μs at 1 GHz to 2.4 kpc (e.g. Crab)
- 1 μs at 100 MHz to ~100 pc

Cosmological Horizon

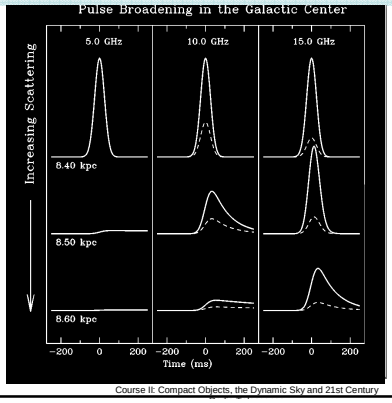
- 1 ms at 1 GHz to z=0.2
- z=1: τ_d ~ 100 ms at 1 GHz (DM=900)

Matter Content of the GC





Pulse Broadening from Galactic Center Transients



Transient Surveys

- Fast
  - Too fast to be sampled by raster scanning (<1 day)
  - Sub-second transients:
    - Produced by compact sources (size < cΔt)
    - Coherent radiation
    - Influenced by diffractive interstellar scintillations
      ⇒ imposed ν-t structure on intrinsic signal
  - Sampled by "staring" for long dwell times
  - Large solid angle coverage needed for rare events
    - Likelihood of detection
    - Completeness level
  - Very high data rates for full FoV analysis
- Slow
  - Durations long enough to be handled with imaging raster scans

Radiometer Noise

Radiometer Equation

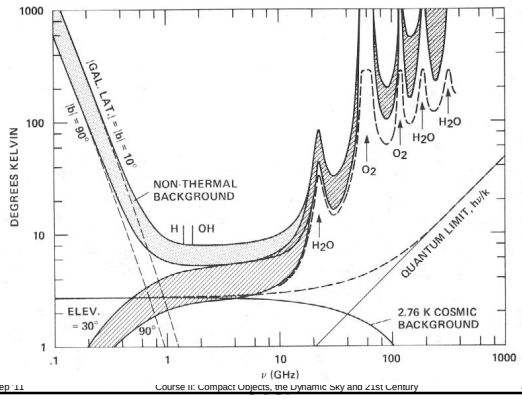
$$\frac{\sigma_T}{T_{sys}} = \frac{\sigma_S}{S_{sys}} = \frac{1}{\sqrt{n_{pol}\Delta\nu\Delta t}}$$

Radiometer variations are analogous to photon counting and readout noise in a CCD detector

n_{pol} = number of polarizations summed (2)
$\Delta\nu$ = bandwidth
Δt = integration time

T_{sys} = system temperature
$S_{sys} = \frac{T_{sys}}{G}$ = system equivalent flux density (SEFD)
$G = \frac{A_{eff}}{2k}$ = gain (K Jy^{-1})
$A_{eff} = \eta_A A_{geometric}$ = effective area
η_A = aperture efficiency ≈ 60%

Background Sky Noise



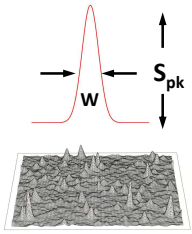
Steady Sources

- Detection of a source requires discrimination from radiometer noise and from source confusion in an image or raster scan of the sky
- Radiometer noise limit:
  - Source flux density S
  - Signal to noise ratio SNR = $S/\sigma_S \geq SNR_{min}$ ~ 5 (e.g.)
  - 100 m equivalent diameter (GBT, EVLA, Effelsberg):
    - G ~ 2 K Jy^{-1} and T_{sys} ~ 30 K → SEFD = 15 Jy
    - $S_{min} = SNR_{min}\,\sigma_S$ ~ 5 x 15 Jy / (2 x 10^9 Hz x 1 s)$^{1/2}$ = 1.6 mJy
  - Arecibo equivalent: SEFD = 3 Jy → S_{min} = 0.33 mJy
  - Square Kilometer Array: SEFD = 0.3 Jy → S_{min} = 33 μJy
  - Longer integration times (e.g. 12 hr): S_{min} ~ 1 μJy

1 sec
1 GHz

Pulsed Sources

- For time variable sources, source confusion is not a factor
- W = the effective integration time when source detection is based on matched filtering
- Bursts have been seen with W as short as 0.4 ns and as long as years



Periodic sour

Periodic sour
filtering can s

Signal: $S(t) = \sum_k A($

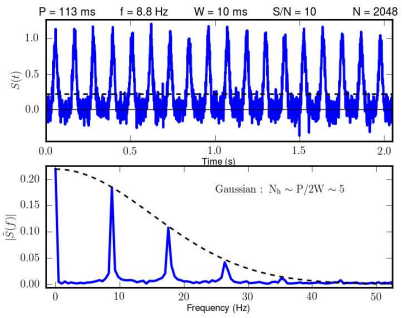
Fourier transform: $\tilde{S}$

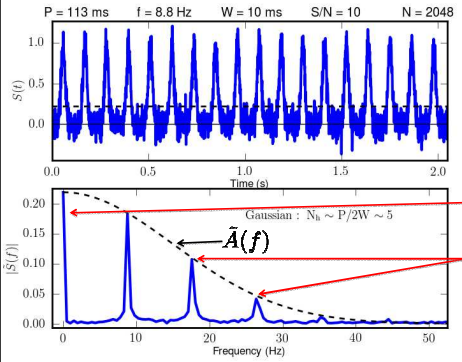
$\tilde{S}(f) = \tilde{A}(f)\sum_k e^{-2\pi}$

$\tilde{S}(f) \approx N\tilde{A}(n/P)$ at

The Fourier transfor

1. A "DC" (zero f
2. A spike at the
3. Harmonics at frequencies n/P
4. The number of significant harmonics ~ P/W = "duty cycle" (W = pulse width, P = period)





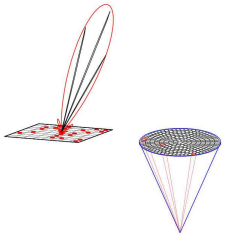
The f=0 component has the same S/N as for a steady source

Harmonics can be summed to increase S/N by a factor ~$\sqrt{N_h}$

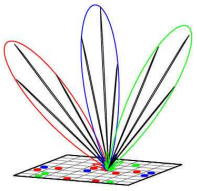
Pulsars: N_h~16 → factor of 4 increase in S/N

Search Modes

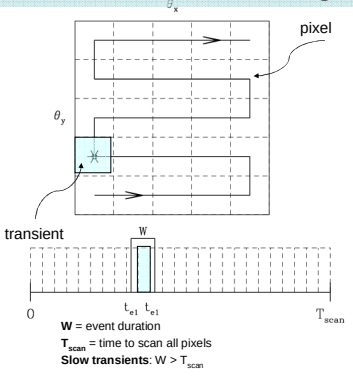
Aperture synthesis + fast dump processing



Fly's eye mode: N antennas in M subarrays or multiple-pixel receivers

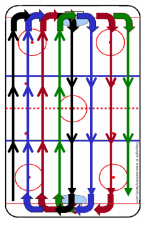


Raster Scanning for RSST



W = event duration
T_{scan} = time to scan all pixels
Slow transients: W > T_{scan}

Different cadences for extragalactic sky and Galactic plane



Example Raster Scan Survey

- 1 deg^2 FoV
- Full sky survey (80% of 40,000 deg^2)
- T_{scan} = 5 days
- T ~ 10 sec = time per sky position
- S_{min} ~ 15 μJy at 10σ with full sensitivity and on axis
- Subarrays reduce the sensitivity but speed up the survey
- Multiple FoVs increase the sensitivity and speed of the survey

GRB radio afterglows

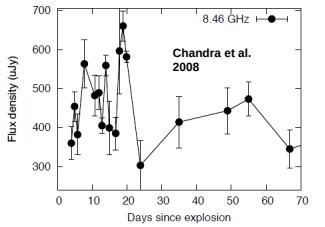
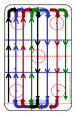


Fig. 3.— Long term light curve at 8.46 GHz showing evidence of interstellar scintillation. This scintillation is refractive in nature and starts dominating once diffractive scintillation quenches (see text for more details).

Survey Metrics

Survey speed for Steady Sources:



- Payoff = number of objects detected to some flux density level in some fixed amount of time
- Steady sources, homogeneously distributed, etc.
  - » Integration time per source = dwell time in survey τ
- Get same metric by looking at rate at which volume or solid angle surveyed:
  - ⇒ SS = FoV (A/T)^2
- Processed bandwidth enters in linearly
  - ⇒ SS = FoV (A/T)^2 B
- Extended survey metric that includes other factors:

$$\mathrm{FoMSS} = B\left(\frac{N_{\mathrm{FoV}}\Omega_{\mathrm{FoV}}}{N_{\mathrm{sa}}}\right)\left(\frac{f_c A_e}{mT_{\mathrm{sys}}}\right)^2$$

f_c = fraction usable antennas
N_{FoV} = number of pixels (PAFs)
N_{sa} = number of subarrays
m = signifcance level (min. S/N)

Survey Metrics

Survey speed for Transient Sources:

- W = transient duration, τ = dwell time in survey scan
- Slow transients: integration time = τ
- Fast transients: (days → ns) integration time = W
- ⇒ New factor on survey metric that accounts for integration time and time-capture probability

$$\mathrm{FoMTS} = \mathrm{FoMSS} \times K(\eta W, \tau/W)$$

$$K(a,x) = \underbrace{\left(1+x^2\right)^{-1/2}}_{\text{Integration time factor}} \underbrace{\left[1-e^{-a(1+x^2)^{1/2}}\right]^{4/3}}_{\text{Probability that} \geq 1 \text{ event occurs from source when pointed at}}$$

K(a,x) ≤ 1

x = τ / W a = ηW, η = event rate/source

See SKA Memo 97

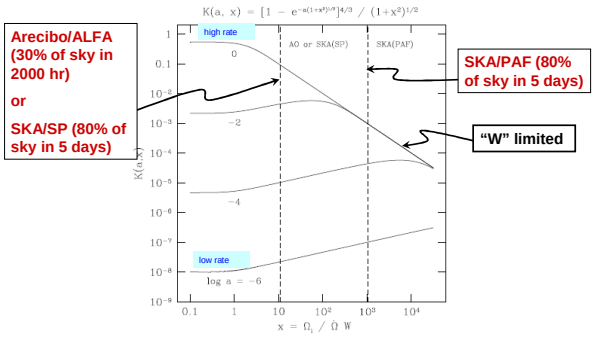


Fig. A16.— Plot of the temporal factor $K(a,x)$ defined in Eq. A10 for several values of a. The vertical lines denote values for $x = \Omega_i T_s/(\Omega_s W)$, where Ω_i is the instantaneously sampled solid angle, Ω_s is the total solid angle surveyed in time T_s, and W is the transient duration. We assume $W = 1$ s in both cases. The leftward line applies to an extragalactic survey using the 7-beam ALFA system with 3.5 arcmin beam widths at Arecibo that surveys 30% of the sky in 2000 hr. The same x is achieved for an SKA system with single-pixel feeds having 1 deg beams that survey 80% of the sky in 5 days. The line labelled "SKA(PAF)" is for the same SKA survey but using a phased-array feed with 100 beams.

Survey Metrics

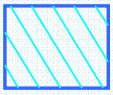
Survey speed for Pulsars ("steady transients"):

Extra factor that depends on P, DM, duty cycle

FoMPSR = FoMSS × harmonic sum factor

$$\mathrm{FoMPSR} = \mathrm{FoMSS} \times h_\Sigma^2(P, DM)$$

$$= B\left(\frac{N_{\mathrm{FoV}}\Omega_{\mathrm{FoV}}}{N_{\mathrm{sa}}}\right)\left(\frac{f_c A_e}{mT_{\mathrm{sys}}}\right)^2 h_\Sigma^2(P, DM)$$



Harmonic sum in pulsar search
Exploits pulse sharpness
Need to minimize pulsar broadening effects:
ISM, orbital acceleration

Another issue for pulsar surveys:
Minimum Contiguous Dwell Time: FFT based searches
⇒ Limitations on tradeoffs between FoV and A/T

Parallel Survey Issues

- Parallel surveys: synoptic survey modes
  - Do as many surveys simultaneously as possible
    - HI, magnetism, pulsars, transients …
  - Relaxes FoV requirements on high volume surveys that require significant total time
  - Puts huge pressure on backend, real-time processors
- Pixelization of the field of view
  - Number of pixels $N_{\mathrm{pix}} \sim 0.85\left(\frac{b_c}{D}\right)^2 \sim 10^{3.8}\left(\frac{b_c/1\,\mathrm{km}}{D/12\,\mathrm{m}}\right)^2$

- Significant collecting area in a core array is needed to keep processing requirements manageable
- Number of operations for pixelization via correlation

$$N_b = 10^{16}\,s^{-1}\left(\frac{f_c}{0.5}\right)\left(\frac{N_a}{4400}\right)\left(\frac{N_{\mathrm{pol}}}{2}\right)\left(\frac{b_c/1\,\mathrm{km}}{D/12\,\mathrm{m}}\right)^2\left(\frac{B}{400\,\mathrm{MHz}}\right)$$

$$

$$$$$

¢¢¢¢¢

Sensitivity vs. instantaneous FoV

$$\Omega_i A_e = \lambda^2$$

$$S_{\nu,\min} = \frac{mT_{\rm sys}}{G\sqrt{2B\tau}} \propto \frac{T_{\rm sys}}{\Omega_i}$$

For:

1 GHz

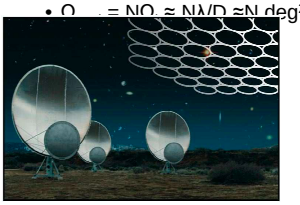
1 sec integration

0.3 GHz bw

25 K, 60%

Fly's Eye Surveys

- Point N antennas in N separate directions
- → total instantaneous solid angle coverage
  - $\Omega_{\rm inst}$ = NΩ$_i$ ≈ Nλ/D ≈N deg^2 for 12 m antennas at 1



No detection of any events like the Lorimer pulse

Inconsistent with Lorimer pulse originating from a cosmological source

Conclusion: Lorimer burst not astrophysical

Burke-Spaloar:

Basic Questions about the Transient Universe

- What will a comprehensive radio survey for transients yield?
  - Large phase space in duration (> ns) , time-frequency signature, amplitude, rate
  - Are there prompt, coherent radio bursts from GRBs?
  - What is the beaming fraction for GRB afterglows based on orphan afterglow events?
- What makes neutron stars intermittent radio emitters
  - RRATs, magnetars, other?
- What new source classes are there?
  - particle events, evaporating black holes, ETI events?
- What is the magnetic field, plasma density and turbulence like in the near and distant IGM? What is the structure of the ionized cosmic web?
  - use fast radio transients to measure time delay dispersion, Faraday rotation and multipath scattering in the ISM and the IGM

Research Plan for Radio Transients

- Comprehensive surveys for radio transients
  - wide fields of view for blind surveys
  - wide range of possible signal strengths
    - can trade sensitivity for field of view for part of phase space
  - high sensitivity for targeted surveys
    - e.g. Galactic center
    - e.g. Virgo cluster (and beyond) for giant pulses from pulsars
  - high time and frequency resolution for dedispersion and characterization of intrinsic time-frequency signatures
- Triggers from multi-wavelength surveys for fast transients
  - fast response needed and transient storage buffers
- Multiwavelength follow up on many time scales

Telescopes & Instrumentation Needed

- Radio arrays from < 100 MHz to > 10 GHz
  - coherent radio sources known over entire range
  - SKA precursor telescopes, SKA Phases 1, 2 and 3
  - Galactic center requires > 10 GHz
  - Transient buffer for triggered retrospective event searches
  - Observational modes for staring and raster-scan observations with different cadences
- Backend instrumentation that allows:
  - full Stokes parameters
  - time-frequency sampling that allows dedispersion to < 1μs resolution (when astrophysically possible), characterization of intrinsic event signatures (flares), and sampling of interstellar scintillation
  - real-time event flagging for fast alerts
- New algorithms for general event signatures
- High-performance computing and networking

Synergies

- Transient surveys across the electromagnetic spectrum and from non-photonic telescopes
- Triggering of GW searches from spin glitches in pulsars and radio intensity events
- Combined radio (> 10 GHz) and ELT transient surveys of the Galactic center
- Joint radio-optical transient statistics and cross filtering of events (e.g. LSST, SKA)
- Similar joint studies with high-energy telescopes with all-sky monitors

Points

Transients cover a huge parameter space, richly populated
- Compact objects, extreme matter states
- Intervening media (IPM, ISM, IGM)

A full census requires telescopes with:
- Widefield sampling (larger Ω_i important for survey completeness)
- High resolution ν-t processing (< ms, > kHz) (RFI excision, intrinsic)
- Low-mid-high sensitivity
- Operation as a radio synoptic survey telescope
- Commensal observations with multiple backend processors
- New algorithms + HPC + Moore's law

Sensitivity can be sacrificed for FoV:
- Flexible subarray modes
- Very bright, but rare bursts ⇒ fly's eye mode (subarray)

Radio transient studies are part of a multi-λ program:
- Existing antennas+multipixel feeds: Arecibo, GBT, Jodrell, Parkes
- Pre-SKA arrays: LOFAR, LWA, MWA, ATA, EVLA, VLBA,WSRT, ASKAP, MeerKat
- Cross-λ triggers (radio ←→ optical, X-ray, γ-ray)
- Cross-λ source classification

Extra Slides

Example Synoptic Cycle for SKA

A 10-day total cycle: variable scanning rates
- Fast scan for extragalactic sky (away from Galactic plane)
  E.g.
  - 1 deg^2 single pixel FoV
  - Full sky survey (80% of 40,000 deg^2)
  - T_{scan} = 5 days
  - T ~ 10 sec = time per sky position
  - S_{min} ~ 15 μJy at 10σ with full sensitivity and on axis
  - Multiple pixel systems (PAFs) increase sensitivity (for fixed total time)
  - Subarrays reduce sensitivity but speed up the survey
- Slow scan for deep extragalactic fields and Galactic plane
- Galactic center: staring mode
- Repeat scans many times
- Break out of scanning mode for targeted observations (10%?)
- Break out for targets of opportunity

Issues for pulsars (~steady amplitudes):
- Need minimum contiguous dwell time for Fourier transforms (e.g. 100 – 1000 s for large-area blind surveys)
- Need adequate dwells for sustained pulsar timing monitoring

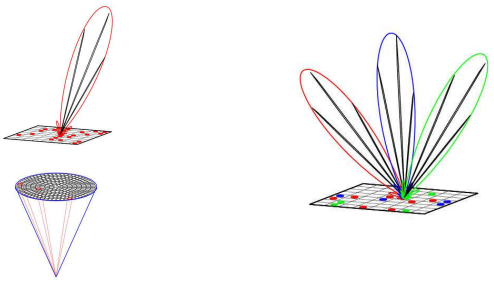
Calibration requirements

Are there solutions for HI, pulsars, transients, magnetism and SETI?

Search Modes

Aperture synthesis + fast dump processing

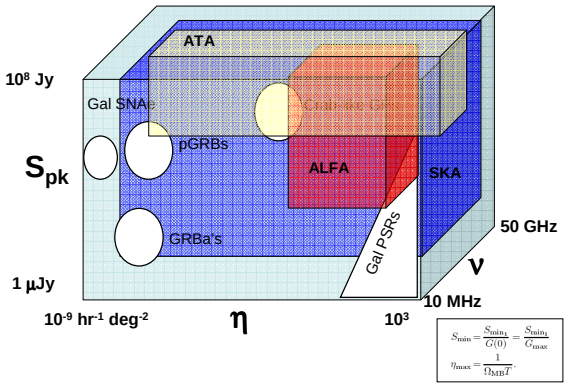
Fly's eye mode: N antennas in M subarrays



Surveys with New Instruments

- ASKAP = Australian SKA Pathfinder
  - 36 12-m antennas with multiple-pixel phased array fee[d]
  - ~ 40 deg^2 instantaneous field of view
  - VAST = survey for slow transients
  - CRAFT = survey for fast transients

Notional Coverage of Phase Space



Points

Transients cover a huge parameter space, richly populated
- Physics of compact objects, extreme matter states
- Probes of intervening media (IPM, ISM, IGM)

Slow transients: easy raster scans

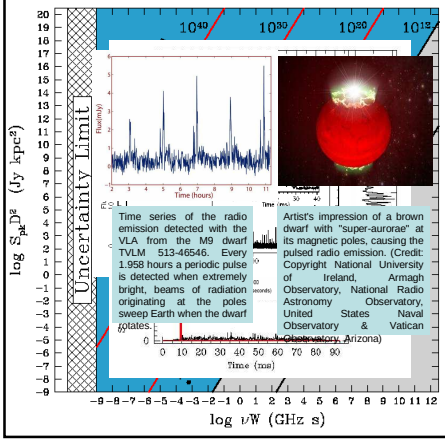
Fast transients: much more difficult

A "full" census requires an SKA with:
- Widefield sampling
- High resolution ν-t processing (< ms, < kHz) (RFI excision, intrinsic)
- Low-mid-high sensitivity

Sensitivity can be sacrificed for FoV
- Very bright, but rare bursts ⇒ fly's eye mode (subarray)

Radio transient studies are a program
- Existing antennas+multipixel feeds: Arecibo, GBT, Jodrell, Parkes
- Pre-SKA arrays:
  - LOFAR, LWA, MW
  - ATA, EVLA, ASKAP, MeerKat

SKA-mid = Radio Synoptic Survey Telescope
- Wide FoV design needed for transients, pulsars, billion galaxy survey
- HPC + data management (real time, archived, multi-λ triggers)



Time series of the radio emission detected with the VLA from the M9 dwarf TVLM 513-46546. Every 1.958 hours a periodic pulse is detected when extremely bright, beams of radiation originating at the poles sweep Earth when the dwarf rotates.

Artist's impression of a brown dwarf with "super-aurorae" at its magnetic poles, causing the pulsed radio emission. (Credit: Copyright National University of Ireland, Armagh Observatory, National Radio Astronomy Observatory, United States Naval Observatory & Vatican Observatory, Arizona)

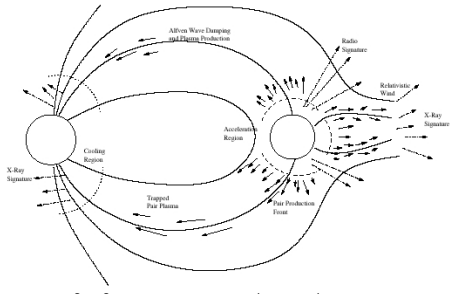
Phase subspace for transients:

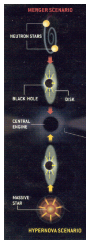
$S_{pk}D^2$ vs. νW

$$kT_b = \frac{2S_{\rm pk}D^2}{(\nu W)^2}$$

W = pulse width or characteristic time scale

Prompt Radio Bursts from γ-ray Bursts



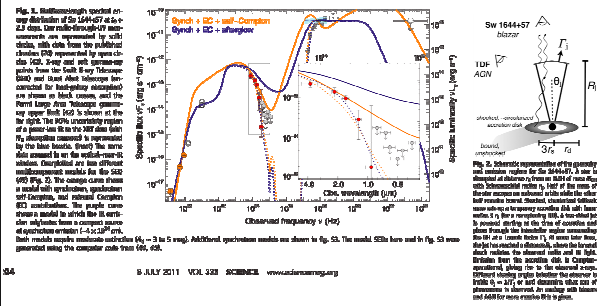


Short bursts: merging NS-NS, NS-BH
⇒ vacua that high-brightness radiation can get through
⇒ plausible radio bursts through reactivation of magnetosphere

Extras

Tidal Disuption Events from Black Holes

Bloom et al. 2011



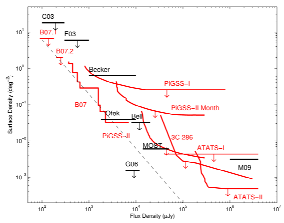


Figure 1: Surface density for other radio transients as a function of flux density from various experiments. Experiments I have carried out (B07, ATATS, FIGSS, 3C286) are shown in red and all the majority of this paper. C05, B07, M09, and Becker surveys were performed by other groups motivated by our discoveries and results. The new set by Metzger et al. (MGB 1999) is closely matched our surveys. The plot shows our projection of the multi-dimensional parameter space for transient searches (sky frequency, cadence, integration time, resolution). Ongoing analysis of the ATA FIGSS survey will improve subject density estimates by one to two orders of magnitude.

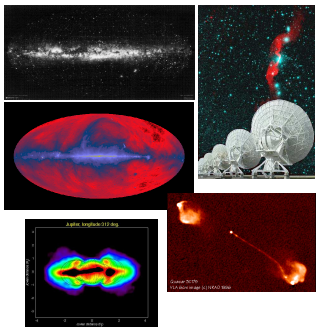
Course II Lecture 5

New Radio Telescope Arrays for Key Science and Discovery

Radio Telescopes:

non-imaging

imaging



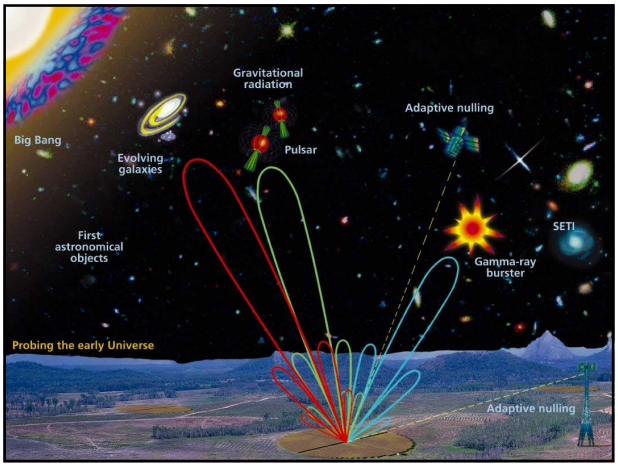
Arecibo VLA

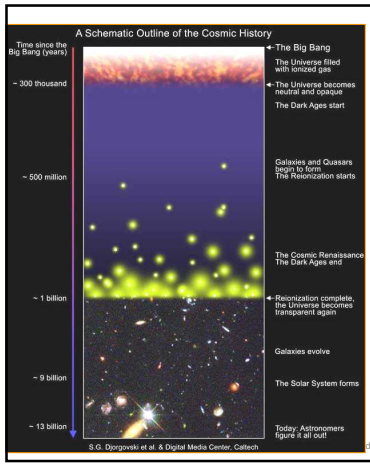
×20 ×50

SKA

Innovations in Radio Telescopes

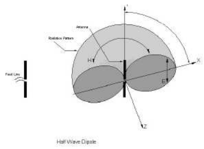
- Where needed?
  - High angular resolution with high sensitivity
  - Wide overall field of view for
    - Fast surveys of the sky (large numbers of objects)
    - Time variable sources (bursts)
- Challenges:
  - Building collecting area cheaply
  - Exploiting Moore's law in digital electronics
  - i.e. steel/aluminum vs. silicon/germanium

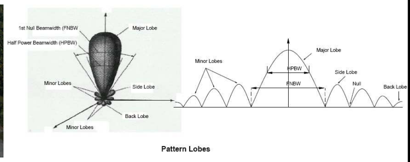




Beam Patterns and Pixels

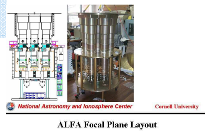
- All telescopes have an angular response to radiation
- Optical/IR/X-ray/Gamma-ray: point spread function (PSF)
- Radio: antenna power pattern $P_n(\theta)$
- A single reflector with a single feed antenna at the focus has one pixel

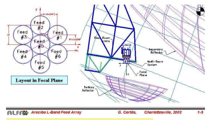


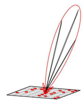


Getting Multiple Pixels

1. Use multiple feed antennas (feed clusters)
   e.g. ALFA = Arecibo L-band Feed Array (7 pixels)
2. Use a phased-array feed system
   Difficult, R&D now a major part of SKA efforts
3. Use arrays of antennas as interferometers and synthesize an aperture

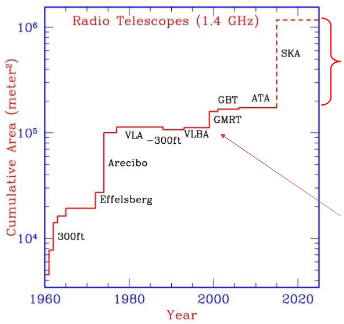






Focal Plane Arrays
"radio cameras"

The Collecting Area Plateau in Radio Astronomy



Recent growth in sensitivity has exploited low-noise devices, developments in digital signal processing bandwidth, and calibration and imaging techniques.

Course II:
Compact Objects, the Dynamic Radio Sky, and 21st Century Radio Telescope Facilities

Jim Cordes
Professor of Astronomy
Cornell University

Five Lectures:

1. Astrophysics of neutron stars and other compact objects
2. Plasma propagation effects (ISM, IGM, ionosphere)
3. Precision imaging and astrometry
4. The dynamic radio sky (transients and variability)
5. New radio telescope arrays for key science and discovery

Cornell University

- Terzan 45, 47 Tucanae

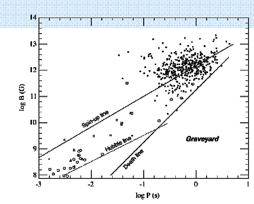


Figure 1. The magnetic fields and periods of known pulsars (see Camilo, this volume for an update). Filled dots indicate isolated pulsars and open circles binaries, both in the galactic disc. Isolated pulsars in globular clusters are shown as triangles and binaries in globular clusters as squares. The spin-up line shows the minimum period to which a neutron star can be spun-up in Eddington-limited accretion. Pulsar activity ceases to the right of the death line, and the spindown age of a pulsar equals 10^{10} y on the Hubble line.

2. Recycling

That the rapid spin of millisecond pulsars may be a result of spin-up due to accretion was conjectured right after the discovery of the first millisecond pulsar B1937+21, which was not even a member of a binary system (Radhakrishnan and Srinivasan 1982). The spin-up process (also called recycling) can achieve a very short spin period if the stellar magnetic field is low, and the accretion rate is high: