RADIO VIEW OF GALACTIC BINARY TRANSIENTS

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Radio transient studies – key science

- Constraints on kinetic feedback via jet-ISM interaction
- Characterization of intervening ionised media via scattering, dispersion and polarization changes
- Precise localisation across very wide fields of view (caveat computational resources)

Majority of transients can be divided in:

- Coherent (Tb up to 1e+30 K), observed in beamformed data; intrinsically much shorter than timescales imposed by scattering and dispersion

- Incoherent synchrotron from explosive events (Tb<1e+12 K). Image-plane transients, “slow” timescales [X-RAY BINARIES]

- Notice: very fast imaging and strong scattering can blur the boundaries; thermal radio emission can be highly variable, too
INCOHERENT TRANSIENTS

Pietka, Fender & Keane 2015
Luminosity-time scale dependence expected, as incoherent synchrotron is limited to a (rest-frame) $T_b \sim 10^{12}$K: the more luminous sources must be physically larger and hence vary more slowly.
INCOHERENT TRANSIENTS

Luminosity-time scale dependence expected, as incoherent synchrotron is limited to a (rest-frame) $T_b \sim 1\times 10^{12} K$: the more luminous sources must be physically larger and hence vary more slowly.

Peak radio lum. scales with flare rise time duration as

$$L_{\text{radio}} \propto \tau^5$$

Flare evolution well described in terms of adiabatically expanding optically thin blob (cf. van der Laan model, 1966)
Transient synchrotron emission from X-ray binaries arises from accretion-related events which are visible in optical, X-rays, etc.

Highest-energy emission escapes while synch. is still optically thick at radio wav., hence radio peaks later (the lower the freq., the later, and at lower fluxes) argues for SKA1-MID bands 4 (2.80-5.18 GHz) or band 5 (4.6-13.8 GHz) deployment.

Decay lasts longer than rise (even at MHz) so radio sky may be dominated by faint sources which are slowly fading.

Fender 2008; Corbel+ 2015
Radio emission from X-ray binaries typically associated to synchrotron radiation from relativistic jets ("quasars for the impatient" cf. R. Blandford)

Hard state: radiatively inefficient, thick disk, steady radio jet on, no equatorial wind

Soft state: thin, radiatively efficient disk, steady radio jet off, mass-loaded equatorial wind [DEGENAAR’S TALK]

see also: Miller+ 12,14; King+ 12,13a,b,14; Neilsen 13, Neilsen+ 12a,b
X-RAY STATES AND RADIO JETS

Ubiquitous steady jets in hard state

- low, persistent flux density (10-50 mJy)
- flat radio-IR spectrum, partially self-absorbed
- 10s of AU
- long lived: months-yrs

Cygnus X-1, Stirling+ 01
X-RAY STATES AND RADIO JETS

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Transient, flaring jets during hard-to-soft transitions

- bright, adiabatically expanding (0.1-10 Jy)
- optically thin
- 100s AU
- short lived: days-weeks

GRS1915+105
Mirabel et al 1994
RADIO EMISSION FROM GALACTIC BLACK HOLE X-RAY BINARIES

Steady jet luminosity
Synchrotron luminosity is at most few % of the total jet power – radio lum.
varies over >7 decades for same black hole

Core radio emission (steady jet) strongly quenched in soft state

Fender, Belloni & Gallo 2004; Fender, Belloni & Homan 2009; Fender & Gallo 2014
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Transient jet luminosity
Peak radio flare luminosity as a proxy for $P_{\text{jet}}$ (cf. Narayan & McClintock 2012; Steiner+ 2013)

GX339-4 2002 radio flare, Gallo+03
Mechanical power from jet-inflated cavities: only available for 3 X-ray binaries (Cyg X-1, SS433, Cir X-1) due to low density contrast (Heinz 2007); more viable for AGN (e.g. Allen+ 2006; McNamara+ 2011)

Cyg X-1:
\[ P_j \sim L_X \sim 10^5 L_{\text{radio}} \], where \( L_{\text{radio}} \) is integrated over the optically thick part only
‘Universal’ radio/X-ray correlation for hard state compact jets (Corbel+ 2003; Gallo+ 2003)

Possible evidence for dual tracks at intermediate Eddington ratios (Coriat+ 2011, Gallo+ 2012, 2014, Corbel+ 2013)

Lower’ track slope may be indicative of efficient accretion (Coriat+ 2011); Neutron stars data close to lower track.
Detection at the low luminosity end virtually hopeless beyond 2 kpc with current gen interferometers (Miller-Jones et al 2011)

Issue of contamination from gyro-synchrotron emission from the companion star below 1e-5 Eddington, where systems may become jet-dominated
BROADBAND SPECTRAL ENERGY DISTRIBUTION - BLACK HOLES

- Possible jet contribution to X-rays via SSC in hard state and quiescence (1E-7 $L_{\text{Edd}}$)
  - GX339-4, XTEJ1118+480, GRO J1655-40 A0620-00, SwiftJ1357.2-0933 with broadband jet-dominated model (cf. Markoff+)

- Integrated jet luminosity comparable to $L_x$

Plotkin+ 2015
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Gallo+2007
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Gallo+2007
BLACK HOLES IN THE ALL-SKY RADIO ASTRONOMY ERA

• SKA1-MID can monitor *all* detected black hole outbursts (up to a few tens per year) all the way down to quiescence.
• A 10 hrs obs. could detect all quiescent black hole binaries up to a distance of 5 kpc.
• With sub-arcsec resolution in band 4- the transient jets could also be resolved from a week after the onset of the radio flare
• Good polarization measurements (linear and circular, with good signal purity) will provide key probes of the (unknown!) composition and geometry of the jets, and the structure of their magnetic fields.

Gallo+2007
RADIO/X-RAY DOMAIN - NEUTRON STARS

Systematic studies of the radio luminosities of accreting neutron stars are far sparser than those for black holes; outburst timescales are faster, making fast scheduling difficult.

Neutron stars systematically less radio loud (Migliari & Fender 2006), also X-ray brighter at same accretion rate (Garcia + 2001; Fender Gallo Jonker 2003)

Tentative evidence for radio:X-ray scaling relation (beware of small dynamic range)

\[ L_r \sim L_x^{1.4} \]

\[ L_r \sim L_x^{0.7} \]
• High B-field does not necessarily imply lower jet power (Migliari & Fender 2006)

• Evidence for jet suppression in soft state, though less extreme (Miller-Jones+ 2010)

• Neutron star studies can also help shed light on whether particles can be launched in a jet at speeds significantly greater than the escape speed of the accretor
Accreting MSPs appear to resemble standard quiescent LMXBs

- Flat radio spectrum
- “Jet dominated” propeller state?
NEUTRON STARS IN THE ALL SKY RADIO ASTRONOMY ERA

- Enhanced sensitivity will enable proper comparison to black hole systems over several orders of magnitude in luminosity, hence elucidating whether radio:X-ray scaling relation hold for NSs, too.
- Study of radio power as a function of magnetic field strength, spin, accretion rate
- As distances and inclination angles for many neutron star X-ray binaries will be directly measurable with the SKA, the combination of two-sided proper motions and detections of the counter-jets should allow for a clean test of whether the pattern speeds and the bulk motions of jets are equal in black hole and neutron star accretors
NEUTRON STARS IN THE ALL SKY RADIO ASTRONOMY ERA

- Highest apparent velocity jet in the Galaxy: Circinus X-1 (15c; Fender et al. 2004)
- Indirect evidence only – missing bona fide, moving, radio-emitting “blobs”
SKA-1 wide-and-shallow and narrow-and-deep continuum surveys.

Fender 2015
**Past:** restricted survey speeds of older generation radio facilities has meant that detections of radio transients lag far behind that which is possible with, for example, X- and gamma-ray instruments.

**Current/future** (LOFAR, MeerKAT, ASKAP – SKA): all sky radio astronomy era - eventually leading to arcsec precision immediate localization. $1 \times 10^5$ image plane transients per year in the coming decade up to several $1 \times 10^8$ with SKA phase 2 (Fender & Bell 2011)
Scaling relation between black hole mass, core radio luminosity, core X-ray luminosity for accreting black hole across the mass scale (stellar to super-massive) [caveat: in while in “hard state”, i.e. steady optically thick synchrotron emission]
FUNDAMENTAL PLANE OF BLACK HOLE ACTIVITY

Scaling relation between black hole mass, core radio luminosity, core X-ray luminosity for accreting black hole across the mass scale (stellar to super-massive)

Miller & Gultekin 2011 (dynamical BH masses only)

Zauderer+ 2011
Cenko+ 2012
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FRB-asssociated fading radio source in $z=0.5$ early type

$L_r \sim$ few $10^38$ erg/s – brighter than any known incoherent emission from stellar-mass objects
Accreting white dwarfs have shown evidence for jets and jet-like shocked, collimated outflows, observed at radio frequencies and interpreted as synchrotron emission, although the brightness temperatures allow for thermal and/or cyclotron emission, too (SKA: better spectral and circular pol).

Regardless, transient jets have been detected in all sub-classes:

- Symbiotic star Z And (Brocksopp et al. 2004)
- Recurrent nova1 RS Oph (Rupen et al. 2008)
- Dwarf nova SS Cyg (Körding et al. 2008)

SKA1- MID will extend the sample of radio dwarf novae out to kpcs, (where optical transient surveys such as LSST will be finding thousands of new dwarf novae; see Drake et al. 2014)
NOTEWORTHY OTHERS. I WHITE DWARFS

Körding et al. 2008
NOTEWORTHY OTHERS. I WHITE DWARFS

Körding et al. 2008
Non-linear radio:X-ray luminosity scaling implies that radio surveys may be more efficient at finding quiescent accreting black holes than X-ray searches (Maccarone 2005)

VLA, can only reach radio luminosities of \( \sim 1 \times 10^{28} \text{ erg/s} \) in Galactic clusters, enabling the detection of the brightest quiescent systems (giant donors or ultracompact sources).

10-hour run in band 4 with SKA1-MID could drop this limit by an order of magnitude, and reducing the upper limit on putative IMBH for the most nearby clusters.
The population of ultraluminous X-ray sources (>1e39 erg/s) in external galaxies (Feng & Soria 2011). Origin:

- Ordinary X-ray binaries accreting at or above the Eddington rate for 10 Msun
- massive stellar-mass black holes (>100 Msun) intermediate-mass black holes (100<M<1e4 Msun)
- neutron stars (Bachetti+ 2014)

Radio emission detected from several such sources, either as jet-blown bubbles around powerful, persistent sources (e.g. Kaaret et al. 2003; Soria et al. 2014), or (in rare cases) as transient jets (Webb et al. 2012; Mezcua+ 2013; Middleton et al. 2013).

Nebulae could be detected out as far as 100 Mpc with SKA1-MID in just a few hours of time.
An estimated $1 \times 10^8$ isolated stellar-mass black holes in our Galaxy, accreting at some low level from the interstellar medium.

A small but significant fraction should be detectable by the SKA as radio point sources with flux densities of a few $\mu$Jy. Would be distinguishable from faint background radio sources by their relatively high proper motions (up to 100 mas/yr).

Such an approach may be the best method of finding the closest black hole to the Earth.
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Simulated SKA2 residual image at 5 GHz with positive-negative emission due to the motion Fender+ 2013.
RADIO TRANSIENTS: RATES & LIMITS

- log $N$ – log $S$ distribution for GHz-frequency radio transients with variability timescales of weeks (from detections + limits)

- Population slope (Bower+ 2007) consistent with a homogenous source population in Euclidean space i.e. $N \propto S^{(-3/2)}$

Fender after Bower+ 2007; 2011
RADIO TRANSIENTS: RATES & LIMITS

\[ N \propto \Omega S^{-3/2} \]
RADIO TRANSIENTS: NEXT GEN

- Rates and upper limits for blind searches for radio transients at GHz frequencies (vs. sensitivities from searching commensally through planned SKA-1)

- Caveat: observation timescales and cadence also very important parameters for such surveys.

SKA-1 wide-and-shallow and narrow-and-deep continuum surveys.

Fender+ 2014
RADIO TRANSIENTS: NEXT GEN

<table>
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<tr>
<th>Instrument</th>
<th>Snapshot rate (deg$^{-2}$)</th>
<th>Rate per year (deg$^{-2}$ yr$^{-1}$)</th>
<th>Yield (yr$^{-1}$)</th>
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<td>SKA Phase 2 (Mid)</td>
<td>$9.7 \times 10^5$</td>
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<tr>
<td>SKA Phase 2 (Low)</td>
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<td>$3.5 \times 10^5$</td>
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<td>MeerKAT</td>
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RADIO TRANSIENTS: 3D LOG N-LOG S

Log $N$ – log $S$ should be improved to incorporate:

• Characteristic timescale of transient behaviour
• Number of different radio frequencies
• Different directions in the sky
“[..] The new generation of radio facilities and approved key science projects should change all of this, with near real time reporting of thousands of transient events per year. This in turn will provide an extremely rich resource for multiwavelength follow up, and the possible opening of a new window on the high-energy Universe.

Prepare for the flood.”

Fender & Bell, *Radio Transients: An antediluvian review*
• Hard state compact jets: no correlation between spin parameter and jet power (Fender Gallo & Russell 2010)

• Transient jets: controversial

• Positive correlation (consistent with BZ) claimed for transient jets

• $P_{\text{jet}}$ from peak radio luminosity of bright radio flare associated with hard to soft state transition

$P_{\text{jet}} = \left(\frac{v}{5 \text{ GHz}}\right) \left(\frac{S_{\nu,0}}{\text{Jy}}\right) \left(\frac{D}{\text{kpc}}\right)^2 \left(\frac{M}{M_\odot}\right)^{-1}$

• Spin from thermal cont. fitting

• Low-mass X-ray binaries only

Narayan & McClintock 12
Steiner, Narayan & McClintock 13
Result sensitive to exclusion of high mass X-ray binary Cyg X-1; Treatment of GROJ1665-40 and 4U1543-47

Large scatter observed in peak radio lum. over different outbursts (though maximum possible lum. is adopted as jet power proxy)

High cadence radio monitoring (e.g. with MeerKAT) needed

See McClintock, Narayan & Steiner 14 for a recent review of the controversy