Searching for the First Generation of Black Holes in Boötes

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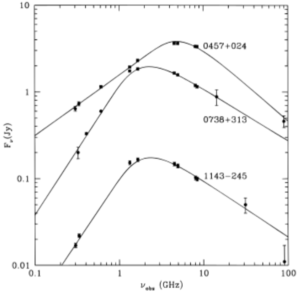
Gigahertz Peaked-Spectrum Sources

- GPS sources, a subset of radio galaxies, are characterized by their peaked spectra and steep spectral indices at high frequencies (O'Dea at el. 1990, 1991).
- Radio emission from GPS sources are dominated by optical thin synchrotron emission in their radio lobes.
- The observed spectral turnover at low frequencies are caused by optically thick synchrotron self-absorption.
- Sources with higher intrinsic turnover frequencies are primarily found at higher redshifts (e.g. de Vries at al. 1997).



Example spectrum of three GPS sources illustrating their peaked spectra. Image from Bicknell et al. (1997)

Science Goal

- We aim is to use LOFAR to search for the first generation of black holes at the center of high-redshift GPS sources.
- Falcke et al. (2004) proposed a survey strategy to search for these sources.
- The proposed strategy involves searching for compact, highly peaked spectrum sources in low frequency (100 - 600 MHz) radio images.
- The search strategy requires images with noise in the order of 0.1mJy/beam and arcsecond resolution.
- Candidates are identified using their spectral shape and confirmed with higher resolution ($\sim 10mas$) observations to find the ultra-compact, low-frequency peaked sources.

The Boötes Field

- Boötes is part of the NOAO Deep Wide Field Survey.
- The field is centered on RA = 14:32:05.7, DEC = +34:16:47.5 covering $\sim 9deg^2$ in the optical and near infra-red.
- Multi-wavelength radio data are available at 74MHz (VLSS, Cohen et al. 2007), 153MHz (GMRT observations, Williams et al. 2013), 325MHz (WENSS, Rengelink et al. 1997), 1.4GHz (FIRST, Richard et al. 1997) and 4.85GHz (GB6, Gregory et al. 1996).
- Additional multi-wavelength data are also available in the X-ray, UV and mid-infrared.
- The AGN and galaxy evolution survey (AGES) measured redshifts for 23 745 galaxies and AGN in the field (Kochanek et al. 2012).

Observing Boötes with LOFAR

- The observation was done using LOFAR's high-band antennas (HBA, 110-190 MHz) on the 2nd of February 2013 between 03:00:00 and 11:00:00 UTC.
- Data were recorded with 1s integrations.
- 37 stations were used, of which 17 were core stations, 13 were remote stations and 7 were international stations.
- Using LOFAR's beam forming mode, one beam was placed on a $\sim 2Jy$ source near the center of the Boötes field while a second beam was used to observe the calibrator source 3c286.
- The available 46.8MHz of bandwidth was split equally between the target and calibrator fields.
- For both target and calibrator, the bandwidth was further divided into 120 sub-bands, each containing 64 channels of 3.05KHz.

Data Reduction

- Pre-Processing:
  - Data are averaged to 10s integrations and one channel per sub-band.
  - All international stations are flagged.
  - All visibilities after 08:00:00 UTC are flagged due to poor data quality.
- GMRT Skymodel for Amplitude and Phase Calibration:
  - Williams et al. (2013) published a Giant Metrewave Radio Telescope (GMRT), 153MHz skymodel of the Boötes field containing 1289 sources, rms noise between two and four mJy/beam and 25" resolution.
  - All sources with flux above 1.0Jy that are located within 2.5deg of the LOFAR phase center were selected.
  - Spectral indices for each source was found using VizieR and included in the skymodel.
  - The final skymodel contained 18 sources.

Data Reduction Cont.

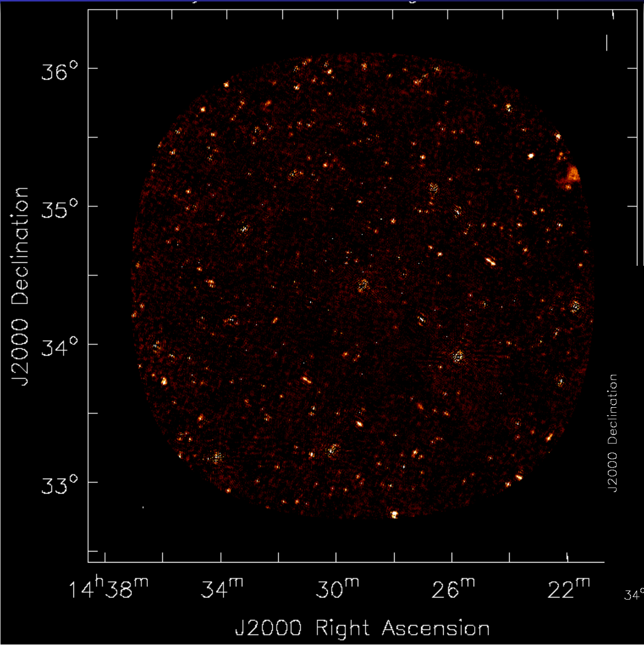
- Calibration:
  - BBS was used to amplitude and phase calibrate each sub-band individually using the GMRT skymodel.
  - All 120 sub-bands were concatenated together and imaged, using AWimager, to produce an image four degrees in diameter.
  - A Gaussian skymodel for the image was made using PyBDSM.
- Phase only self calibration was done on each sub-band individually using the extracted Gaussian skymodel.
- Five images were made, one using the full bandwidth and four using a quarter of the bandwidth each.
- Skymodels for the images were made with PyBDSM using an island threshold of $3\sigma_L$ and pixel threshold of $5\sigma_L$ and $7\sigma_L$ for the image with all sub-bands and the images made using a quarter of the sub-bands respectively.

Image Details

Image Name	Bandwidth Used	Central Frequency (MHz)	Noise (mJy/beam)	Restored Beam
$LOFAR_{all}$	Full bandwidth	153	~ 1	$14.6'' \times 11.5''$
$LOFAR_1$	First quarter	144	~ 3	$16.7'' \times 12.5''$
$LOFAR_2$	Second quarter	150	~ 2	$14.9'' \times 11.7''$
$LOFAR_3$	Third quarter	156	~ 2	$13.8'' \times 11.1''$
$LOFAR_4$	Fourth quarter	162	~ 2	$13.4'' \times 10.7''$

- The image noise and resolution are a factor of two to three above the predicted thermal noise and resolution.
- The problem can likely be addressed by doing additional rounds of self calibration.

Image Details Cont.



Images of the field and central sources made using the full bandwidth.

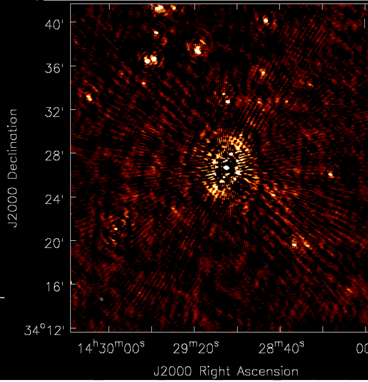


Image Quality

- The sources in $LOFAR_{all}$ were matched to the Williams et al. (2013) catalog with STILTS using a 14.5" search radius.
- The LOFAR catalog was resolution scaled to match the 25" resolution of the GMRT catalog.
- All sources with signal to noise ratio (SNR) below ten were excluded from further analysis.

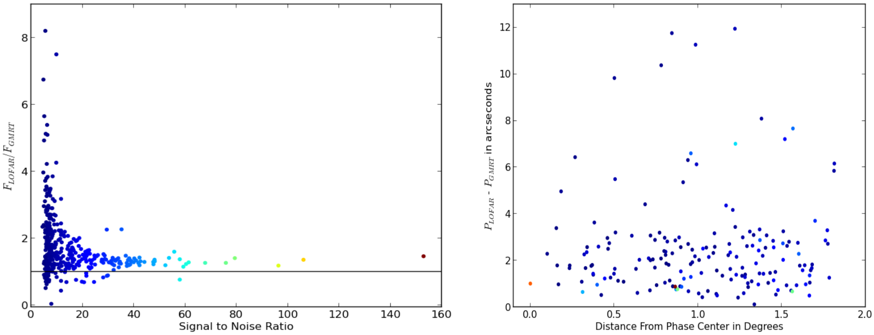
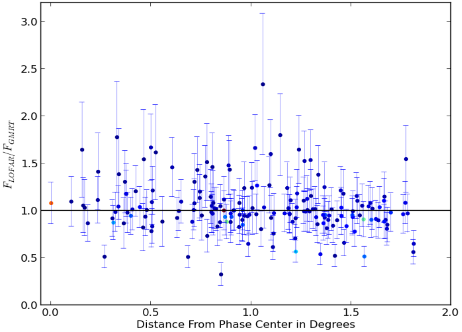
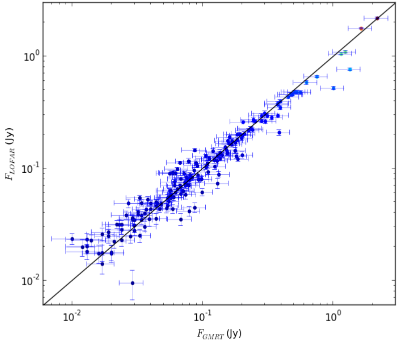


Image Quality Cont.

- F_{LOFAR}/F_{GMRT} is independent of the distance of the source from the phase center.
- The relationship between F_{LOFAR} and F_{GMRT} does not change as a function of F_{GMRT}.
- Flux values were corrected by a factor of 0.73, the inverse of the median of F_{LOFAR}/F_{GMRT}.

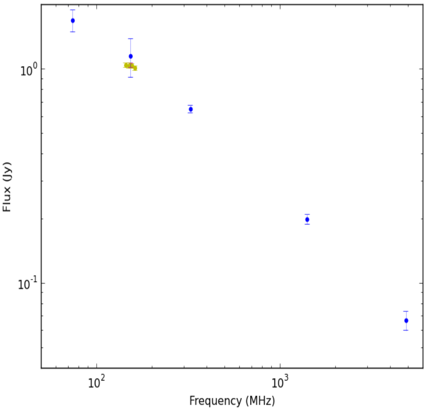


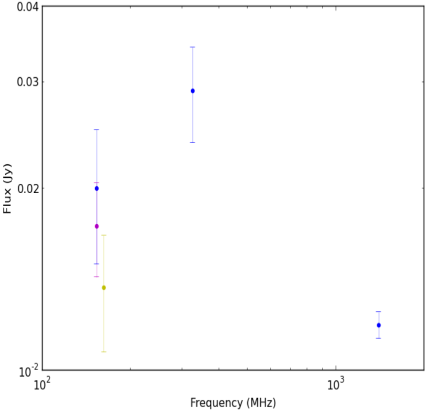


Spectral Plots

- STILTS was used to match the sources in $LOFAR_{all}$ to the VLSS, WENSS, FIRST and GB6 catalogs.
- For each pair of catalogs, a search radius of half the resolution of the catalog with the lowest resolution was used.
- $LOFAR_{all}$ was matched to $LOFAR_1$, $LOFAR_2$, $LOFAR_3$ and $LOFAR_4$ using K3Match (Schellart. 2013) with a search radius of 7.5".
- For each source in $LOFAR_{all}$, the flux value of the matched source was used if and only if a one to one match was found.
- For each sources, a separate spectral plot was generated.
- If no match was found in the VLSS catalog, the VLSS detection threshold of 0.7Jy was used in the spectral plot.
- If a source was found to have SNR below ten in any of the LOFAR catalogs, the flux for that catalog was not included in the spectral plot.

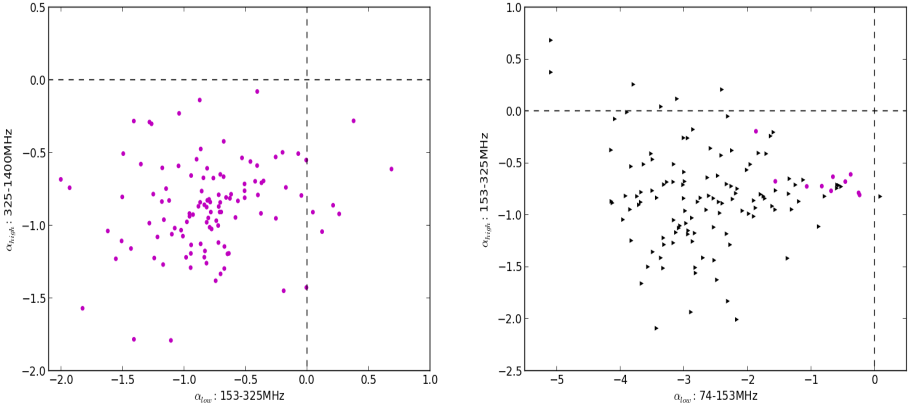
Spectral Plots Cont.





Spectral plots of a source with regular spectrum (left) and a source with a peaked spectrum (right). Flux values for VLSS, GMRT, WENSS, FIRST and GB6 are shown in blue, $LOFAR_{all}$ is shown in magenta and $LOFAR_1$ to $LOFAR_4$ are indicated in yellow.

Colour-Colour Diagrams



Two colour-colour diagrams made using the LOFAR, WENSS and FIRST catalogs (left) and VLSS, LOFAR and WENSS catalogs (right). Values shown as black triangles are found using VLSS upper limits, the true value is located at higher values along the x-axis.

Future Work

- Improve the image quality (increase the resolution and reduce noise).
- Determine the cause of the offset between the LOFAR and GMRT flux values observed in some sources.
- Make a selection of compact, highly peaked spectrum sources.
- Re-observe the selected sources to exclude variable sources and determine their size.

Thank you for listening.