Star-forming galaxies at high redshift

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The link between star formation and radio luminosity

- Massive stars form core-collapse supernovae after $\sim$ 30 Myr.
- $\sim$ 10% of supernova energy accelerates a diffuse electron population.
- Interaction with galactic B-field: non-thermal synchrotron radiation.

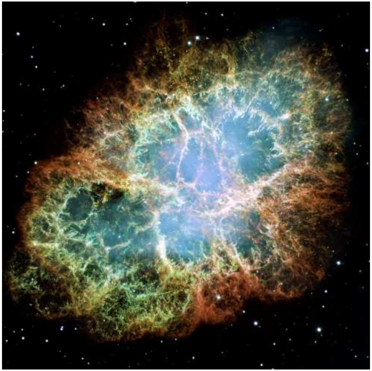

Figure: Crab Nebula (NASA/ESA).

Using radio luminosity as a SFR tracer

- Non-thermal radio luminosity unaffected by dust grains; this is the biggest uncertainty in the use of optical / IR tracers.
- AGN activity can also produce radio emission; this can be overcome by sufficient photometric information.
- Commonly-used relationships (e.g. Condon & Yin 1990; Bell 2003) rely upon observations of local galaxies.
  - A change in the dominant source population, variations in electron confinement, or B-field evolution could all affect the SFR-radio luminosity relationship.

The Spitzer Wide-area InfraRed Extragalactic survey

- Six fields covering 49 deg^2 with low IR background.
- Legacy survey – all optical and IR data is public (*ugriz*; 3.6, 4.5, 5.8, 8, 24, 70, 160 μm; $\sim$ 1 million sources).
- Band-merged and photo-*z* catalogues are available (Surace et al. 2005, Rowan-Robinson et al. 2008).

Figure: Spitzer Space Telescope (NASA / JPL-Caltech).

GMRT observations of the SWIRE fields

- 610 MHz observations of the three northern SWIRE fields (Garn et al. 2008a, b, 2009).
- 20 deg^2, typical noise 40 – 90 μJy beam^{-1}.
- 510 galaxies with SFR estimates, photo-z, and detections at 24 μm, 70 μm and 610 MHz.

Figure: Two of the GMRT antennas.

Removing AGN contaminants

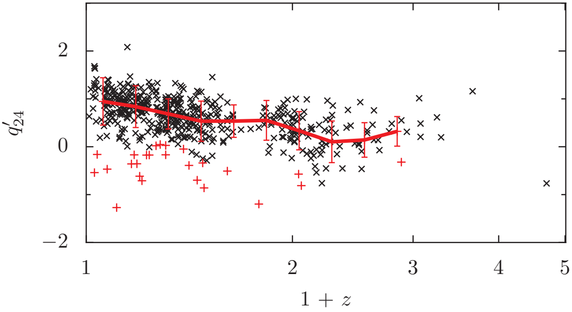

Figure: The IR / radio correlation used as a diagnostic of source type.

$$q'_{24} = \log_{10}\left(\frac{S_{24}}{S_{610}}\right)$$

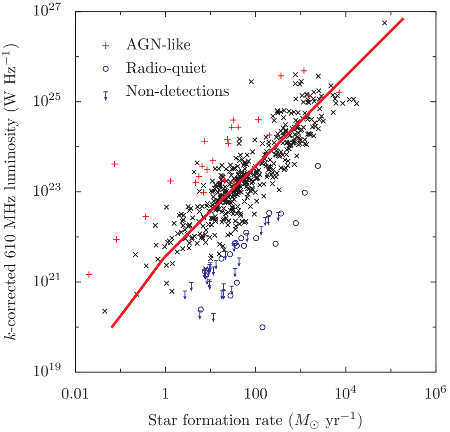

Figure: The Bell (2003) relationship agrees well with the data, after k-correction and shifting to 610 MHz.

Radio-quiet sources

- 20 sources deviate by $> 2\sigma$, 48 more significant non-detections.
- Various explanations:
  - recent starburst activity
  - loss of radio flux
  - incorrect SFR estimation
- 45% have $z_{\mathrm{spec}} \neq z_{\mathrm{phot}}$, other SFRs also appear wrong; poor template-fitting is likely to be the problem.

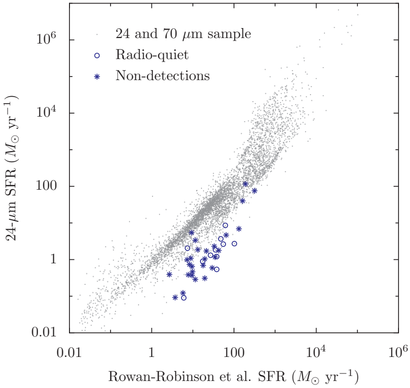

Figure: SFRs from full SED fitting, and from a 24-μm relationship (Rieke et al. 2009).

Redshift evolution of ‘specific radio luminosity’

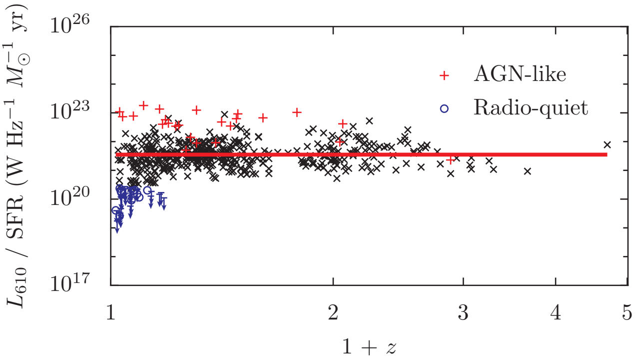

Figure: The specific radio luminosity of galaxies against redshift.

No significant deviation away from the Bell (2003) relationship up to $z = 2$ (peak of star formation in the Universe).

SFR evolution of ‘specific radio luminosity’

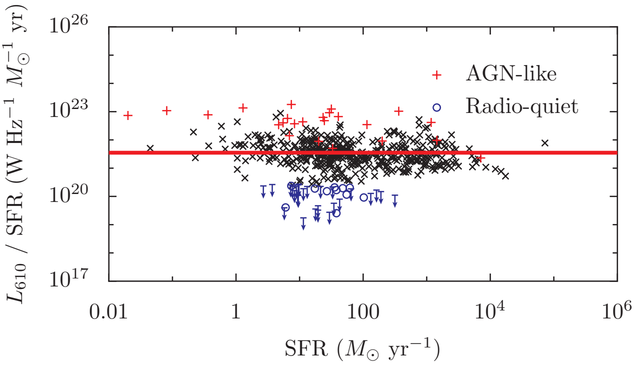

Figure: The specific radio luminosity of galaxies against SFR.

No significant deviation away from the Bell (2003) relationship for SFR between 1 and 10^4 $M_\odot$ yr^{-1}.

Implications of this study

- The local relationship between low-frequency radio luminosity and SFR can be applied sucessfully to galaxies undergoing energetic starbursts at high redshift, as well as to quiescent galaxies in the local Universe (Garn et al. 2009).
- The SFR history of the Universe can be calculated successfully from radio observations (e.g. Haarsma et al. 2000, Seymour et al. 2008), without the significant correction factors required for optical or IR tracers.

The next generation of radio telescopes, such as LOFAR and the SKA, will be able to measure the SFR of the Universe out to much higher redshift.

Observing beneath the noise: Stacking

- Radio surveys can only detect the brightest star-forming galaxies – about 1% of the SWIRE galaxies were detectable in the GMRT surveys.
- Survey depth scales as $\sim 1/\sqrt{\tau}$, so $10\times$ deeper requires $100\times$ more time (or a better telescope).
- However good the telescope, we will always want to push the boundaries of what we can detect.

Stacking allows you to probe beneath the noise level.

Stacking methods – I.

Take the known location of sources from some other survey, and select a sample of interest. Then, either

- Measure the radio flux within an aperture centred on each location, and look at the distribution of measured flux;
  - Individual measurements are dominated by noise.
  - Statistical properties of the distribution will be robust.

  or
- Make 'cut-out' radio images centred on each position, and stack these images together to find the appearance of the 'typical' source.
  - Measure the flux from this stacked image directly.

These two methods give the same results.

Stacking methods – II.

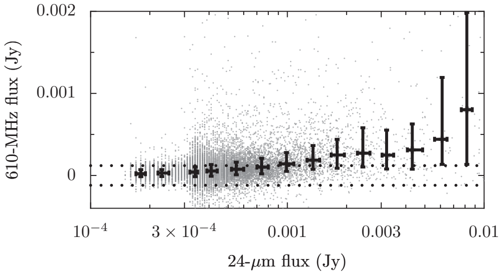

Figure: Distribution of radio flux density from a 610-MHz image of the Spitzer xFLS field (Garn et al. 2007).

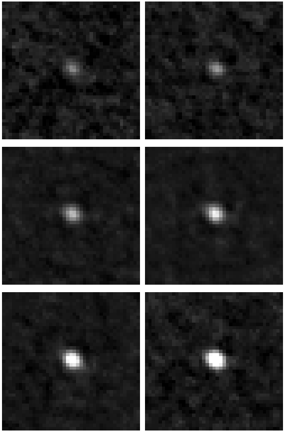

Figure: Stacked images.

Cautionary notes

- Use median stacking – this is robust to a few outlier sources.
- Radio images are made with 'cleaning'; this flux redistribution has unknown effects on the statistical properties of the image.
- A stacking bias may exist (White et al. 2007; Garn & Alexander 2009), leading to a fractional loss of flux from stacked sources. This can be overcome through observations of the same field at multiple depths.

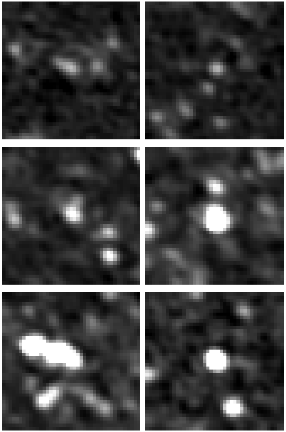

Figure: Mean stacking

Stacking and LOFAR

The tiered nature of LOFAR surveys is ideal for stacking, and their overlapping nature will allow consistency checks to be made.

- The Tier 1 'Large-Area' survey will permit the radio properties of faint, rare objects, otherwise inaccessible to LOFAR, to be studied at multiple frequencies.
- Tier 2 regions already have superb multi-wavelength data, and locations of millions of galaxies and AGN are known. Stacking allows the low-frequency properties of these faint sources to be examined, separated by characteristics such as redshift, optical colour, morphology, ...
- The Tier 3 regions will be some of the deepest radio surveys in existence: stacking extends their effective depth by a further order of magnitude.

Summary

- Radio luminosity traces SFR out to at least $z = 2$, and for galaxies undergoing SFRs of $1 - 10^4 \ M_{\odot} \ \mathrm{yr}^{-1}$.

- Stacking is a useful technique to extend the effective depth of LOFAR surveys, and can be applied to populations ranging from extremely rare objects through to common, but radio-faint distant star-forming galaxies.