Tracing the Ancestry of Galaxies (on the land of our ancestors)
Proceedings IAU Symposium No. 277, 2010
C. Carignan, F. Combes & K.C. Freeman, eds.

doi:10.1017/S1743921311022502

What Radio Astronomy Can Tell us about Galaxy Formation

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Abstract. Radio astronomy, broadly interpreted, has made important contributions to the study of galaxy formation and evolution. Maps of the cosmic microwave background provide information on the seeds of large-scale structure, in addition to refined values of the cosmological parameters. Examples of contributions from more conventional radio astronomy include:–The use of radio observations to track star formation rates since they are not affected by dust obscuration as optical/UV observations are, and the use of molecular line observations to make purely "radio" redshift determinations.

Keywords. radio continuum: galaxies, galaxies: evolution.

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1. Introduction

The value of radio frequency spectral line studies (including those of HI and CO lines) in understanding galaxy structure, dynamics and formation is indisputable and well attested by other papers in this volume. Let me add only that the CO lines allow us to measure redshifts using radio techniques alone. A potential drawback to the use of CO lines is the difficulty of identifying just which CO line is involved. That problem is solved in part by the use of radio-only photometric redshifts as pioneered by Carilli & Yun (1999). These provide rough values of z, allowing us to determine which CO line is present, and thus to pin down z exactly.

What, however, can radio-frequency *continuum* observations contribute? I will briefly list some contributions of continuum radio astronomy to the study of galaxy evolution, beginning with observations in the cosmic microwave background, then turning to more conventional radio astronomy. As I go, I will identify some open questions and make a couple of suggestions for future investigations using radio astronomical techniques.

2. Cosmic Microwave Background (CMB) Studies

Detailed studies of the power spectrum of fluctuations in the CMB have contributed substantially to making cosmology a precision science. CMB observations by themselves can determine parameters such as the Hubble constant, the density of Dark Matter, the baryon density and the spectrum of primordial density perturbations–all to an accuracy of a few percent (Komatsu *et al.* (2011); Dunkley *et al.* (2010); and references therein). One instance is the bias parameter σ_8: combining WMAP and ACT data gives 0.82 ± 0.04 (Sehgal *et al.* (2010)), and the SPT group finds an even lower value, 0.75 ± 0.02 (Lueker *et al.* (2010)). The Planck mission, with its higher sensitivity at a wider range of angular scale, will soon sharpen the values of many of these parameters. These cosmological parameters in turn underlie all simulations of large-scale structure, as discussed here by Silk. CMB observations also provide some hints as to the *amplitude* of the density fluctuations at $z \sim 1000$ that later give rise to cosmic structure. The CMB, however,

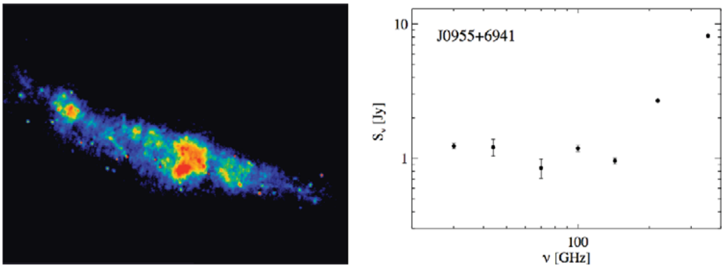

Figure 1. A cm-wavelength radio image of a star-forming galaxy, M82, and its microwave spectrum as measured by ESA's Planck mission (astro-ph/1101.1721). The slight upward bump at 100 GHz may be caused by CO line emission entering the Planck 100 GHz band.

measures the amplitude of baryon perturbations, not the larger amplitude Dark Matter perturbations. Thus the finding of Eisentstein *et al.* (2005) of a feature in the angular distribution of galaxies directly linked to a prominent peak in the CMB power spectrum was particularly important. We are now able to connect the properties of the Universe at a redshift of 1000 to currently observed large-scale structures.

More fundamentally, I'd say, our understanding of the early Universe from CMB studies supports the use of simple linear theory, with gravity as the driving force, to explain the early evolution of structure. Gastrophysics, with all its complications, comes later.

A useful by-product of increasingly sensitive searches for CMB fluctuations on small scales is a better understanding of the counts of radio sources at high frequencies (e.g. Marriage *et al.* (2010), and references therein).

3. Contributions of Radio Astronomy to the Understanding of the Evolution of Individual Galaxies

Let me begin with a slight simplification by claiming that there are just two basic classes of microwave and submillimeter continuum emission from galaxies. First, there is extended synchrotron, free-free and dust reemission associated with star formation and the supernovae that result from it. Such radio emission is present at a low level in all galaxies, and much more strongly in star forming systems such as M82 (Fig. 1). Very roughly, the morphology of radio emission resembles that in the optical. At centimeter wavelengths and longer, the emission is dominated by synchrotron; shortward of $\sim$1 mm, dust reemission takes over. Free-free emission may in some cases be detected in the "valley" at intermediate wavelengths.

Quite different is radio emission associated with active galactic nuclei. Here, the synchrotron process dominates, and the morphology is both complex and disconnected from the optical properties of the emitting galaxy. Radio structures associated with AGN activity include a core (frequently with a flat radio spectrum), jets, and lobes arising from the interaction of jets with the ambient medium (the lobes typically have steep spectra). The division into two classes is not absolute: some starforming galaxies, for instance, also display evidence of AGN emission.

4. Two Important Relationships

It has been recognized for more than 25 years that there is a crucial, and slightly mysterious, correlation between the FIR and radio luminosities of ordinary and starforming galaxies (Helou *et al.*, 1985). This is usually expressed as $S_{1.4} = 10^{-q} S_{FIR}$, where $S_{1.4}$

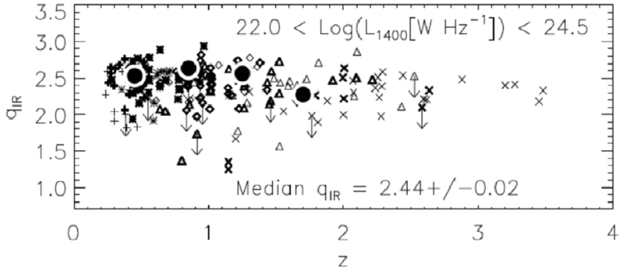

Figure 2. A plot from Ivison *et al.* (2010) showing the relative independence of the index q on redshift.

is the radio frequency flux density measured at 1.4 GHz and S_{FIR} is the far infrared flux, generally measured at ~80 μ. With the usual choice of FIR wavelength, $q \sim 2.3$. This simple linear relationship holds over a very wide range of luminosity from ordinary, radio quiet spirals to ULIRGs (see, for instance, Crawford *et al.* (1996), and Morić *et al.* (2010)). Emission associated with AGN activity violates this relationship, so care must be taken to exclude the AGN-related component (e.g., by excluding emission from a bright, unresolved radio core).

The exponent q in addition to being independent of source luminosity seems to be largely independent of redshift, as shown in Fig. 2. If so, there are interesting consequences for galaxy and star formation. The physical basis for the linear relation of the equation above is presumed to be that star formation produces both the dust reemission that dominates the FIR luminosity, and the supernovae that give rise to the relativistic electrons that in turn produce synchrotron radiation at radio wavelengths. The stars that produce supernovae (say $M > 8M_o$), however, have a different range of mass from those that dominate the UV and optical emission that is thermalized by dust to produce the FIR. If q is independent of z, then it follows that (a) the efficiency of optical/UV absorption and consequent reemission must remain constant, and (b) the upper end of the IMF must also remain constant. [Suggestions for research projects:–it would be useful to make these arguments both more quantitative and more precise. What limits on the evolution of the upper end of the IMF can be fixed by using plots of $q(z)$ like Fig. 2? Is there any correlation between q and the dust temperature that might hint of a violation of a simple linear correlation?]

If we accept the independence of q from either z or L, we can use radio observations alone to measure the star formation rate (SFR) and the function of redshift; that is, we can construct a radio-only Madau diagram (Madau *et al.* (1996), and, specifically, Haarsma *et al.* (2000) for such an attempt). This approach requires a further assumption that the FIR luminosity is tightly linked to the starformation rate, but has the advantage of needing no correction for dust extinction. [Suggested research projects:–since we now know the cosmic infrared background with some precision (see the recent work based on Planck measurements by the Planck collaboration, 2011), can we use the radio/FIR correlation to determine the fraction of the radio wavelength background due to star-forming galaxies as a function of redshift–and thus find the amount of radio background due to AGN? Such an attempt was made by Haarsma & Partridge (1999), but needs to be updated. Useful data is supplied in Moric *et al.* (2010). The results in turn could refine and/or confirm models of radio source contamination of the CMB (e.g., DeZotti *et al.* (2005)). Finally, since we now have redshifts for many more radio sources, an improved radio-only Madau diagram could be constructed; the one provided in Haarsma *et al.* (2000), while generally in agreement with current versions of the Madau diagram obtained from optical observations, is rough, and appears to overestimate the star formation rate at $z = 1 - 2$.]

More briefly, a second crucial and (to me) slightly mysterious relationship is the connection between the mass of a central Black Hole in a galaxy and an appropriate measure of the halo mass or velocity dispersion (e.g., Gebhardt *et al.* (2000)). Richstone (2004) among others has used this relation to estimate the density of AGN in the Universe, and hence the density of optical and X-ray radiation produced by AGN. [Research suggestion:–extend this work, calculate the radio wavelength energy density, and compare it to the measured radio and sub-millimeter backgrounds, which we know are made up essentially of AGN emission and the emission associated with star formation.]

5. Conclusions

I have either pointed out or alluded to a number of ways in which radio astronomy might usefully contribute to subjects or questions addressed in this Symposium, omitting line emission, since that is covered in many other papers in this volume. I have also been deliberately speculative in section 4 to open up some possibilities for further research. Finally, I would simply remind readers that one of the main driving forces behind the construction of ALMA was its utility in investigating galaxy formation. Radio astronomy has a bright future in the field covered by this Symposium!

6. Acknowledgments

I would like to thank the organizers for the opportunity to visit Burkina Faso. Some of the research mentioned here was supported in the past by an NSF award to Haverford College, AST06-06975; my attendance at S277 was supported by Haverford College funds.

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