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A Radio View of the Sky: the Cosmic History of Star-Forming and AGN Galaxies

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Abstract. We explore the cosmic evolution of radio detected star forming (SF) galaxies and active galactic nuclei (AGN), drawn from the VLA-COSMOS survey, out to $z = 1.3$. We present the 20 cm radio luminosity function for these populations, and find that SF galaxies evolve much more rapidly than low-power radio AGN. Our results imply that weak radio AGN ($L_{1.4GHz} \lesssim 5\times10^{25}$ W Hz^{-1}) occur in the most massive galaxies already at $z \sim 1$. They may significantly contribute to the heating of their surrounding medium and thus inhibit gas accretion onto their host galaxies, as recently suggested for the 'radio mode' AGN feedback in cosmological models.

1. Introduction

Radio activity from active galactic nuclei (AGN) has recently been invoked in cosmological models as a significant ingredient in the process of galaxy formation ('AGN feedback'). Given that, in the past, cosmological models led to a systematic over-prediction of the high-mass end of the galaxy stellar mass function, the implementation of gas heating through energetic radio outflows – the 'radio' mode – resulted in a good reproduction of well many observed galaxy properties (e.g. the galaxies' stellar mass function, color bimodality; Croton et al. 2006, Bower et al. 2006). The first observational evidence for 'radio mode' feedback in the context of galaxy formation has been found by Best et al. (2006) based on a local sample of galaxies. However, to date it is unclear how this mode evolves with cosmic time.

Radio emission from extragalactic sources at 1.4 GHz (20cm) is dominated by the radiation from AGN and SF galaxies. Hence, a reliable SF/AGN identification is required for such studies. Combining the VLA-COSMOS 20 cm Large Project (Schinnerer et al. 2007) with the rich COSMOS (X-ray to radio) data-base (Scoville et al. 2007) we have developed a robust method to separate SF from AGN galaxies in the faint radio population (see Smolčić et al. 2006, 2008 for details). This method allowed for a robust identification of ~ 340 SF,

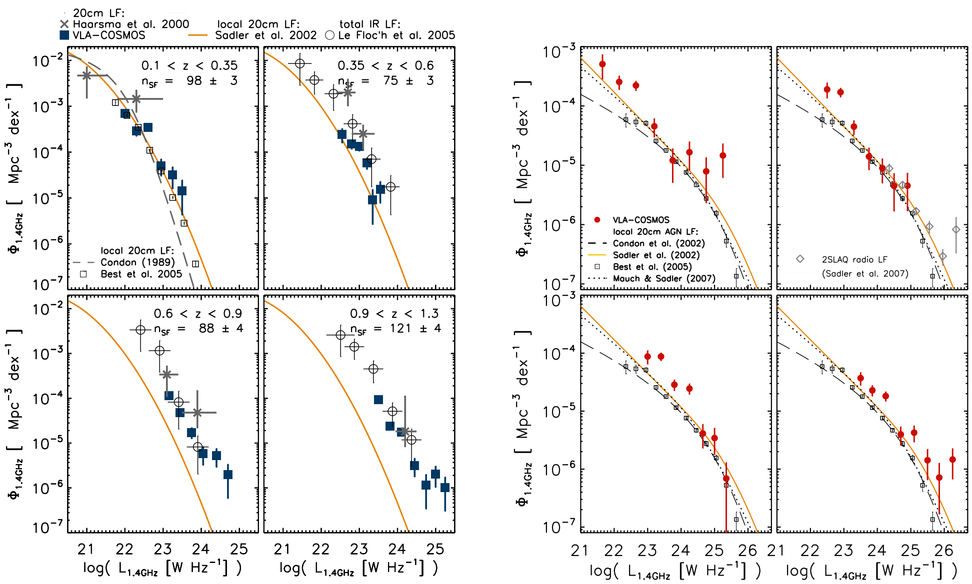

Figure 1. 20 cm luminosity functions for star forming (left; filled blue squares) and AGN (right, filled red dots) galaxies in the VLA-COSMOS survey, shown for four redshift ranges indicated in the panels. We compare the volume densities with other results (indicated in the panels). For more details see Smolčić et al. (2009a, 2009b).

and ~ 600 AGN (Seyferts, LINERs, absorption line systems; quasars excluded) in the VLA-COSMOS field ($i_{\rm AB} \leq 26$) out to $z = 1.3$. Here we utilize these samples to present their cosmic evolution, and investigate the link between star-formation and AGN activity in galaxies, as well as 'radio mode' feedback as a key process for massive galaxy build-up.

2. 20cm Luminosity Functions of VLA-COSMOS SF and AGN Galaxies

Using the $1/V_{\rm max}$ method we derive the 20 cm luminosity functions (LFs) for the VLA-COSMOS SF and AGN galaxies in 4 redshift bins (see Smolčić et al. 2009a, 2009b for details). In Fig. 1 we compare them to various findings in the literature. Our LFs in the lowest redshift bin agree well with the local LFs for both SF and AGN galaxies. This is quite remarkable as a) our identification method is based only on photometry contrary to the spectroscopic selection performed by the other studies (e.g. Sadler et al. 2002), and b) the 2□° COSMOS field samples a significantly smaller comoving volume at these low redshifts compared to the almost all-sky surveys used by the other studies. Within the errors our lowest-redshift LFs seem to be best represented by the local SF/AGN LFs derived by Sadler et al. (2002).

3. Cosmic History of Radio Selected SF and AGN Galaxies

The evolution of an astrophysical population is usually parameterized by monotonic density and luminosity evolution of its local luminosity function. As described in detail in Smolčić et al. (2009a, 2009b), we constrain the evolution of the VLA-COSMOS a) SF galaxies by assuming pure luminosity evolution, but using two initial local LFs (Condon 1989, Sadler et al. 2002), and b) AGN by separately assuming pure luminosity and pure density evolutions using the Sadler et al. (2002) local LF for AGN galaxies.

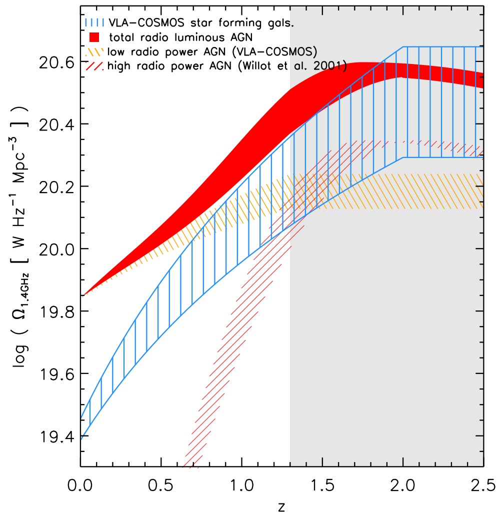

Figure 2. Evolution of the comoving 20 cm integrated luminosity density ($\Omega_{1.4\mathrm{GHz}}$) for *all* radio AGN (filled red curve) and star forming galaxies (vertically blue hatched curve) since $z = 2.5$. The evolution of $\Omega_{1.4\mathrm{GHz}}$ for the total AGN population is a superposition of the evolution of weak (VLA-COSMOS; orange hatched curve) and powerful (model taken from Willott et al. 2001; red hatched region) radio power AGN. The light-gray shaded area of the plot shows the redshift range where the evolution of the VLA-COSMOS AGN and star forming galaxies has been extrapolated ($z > 1.3$; see text for details).

At a specific cosmic time the integrated comoving luminosity density (i.e. an integral over the LF at redshift z) represents the total power per unit comoving volume of a given astronomical population. Thus, if divided into distinct populations it traces their relative contribution to the overall power output at a given redshift.

Black hole growth, especially merger driven growth, is expected to be linked to starburst activity (e.g. Sanders & Mirabel 1996). Thus, in Fig. 2 we compare the evolution of the integrated comoving 20 cm luminosity density for the radio luminous SF and AGN population. Beyond $z = 1.3$ the evolution of the VLA-COSMOS populations has been extrapolated (see Smolčić et al. 2009b). The evolution for powerful radio AGN ($L_{1.4\mathrm{GHz}} \gtrsim 10^{26}$ W Hz^{-1}), not present in the VLA-COSMOS radio-optical sample, has been constrained using a model based on the 3CRR, 6CE, 7CRS samples (Willott et al. 2001).

The integrated comoving 20 cm luminosity density for radio luminous SF and AGN galaxies appears to evolve coevally at high redshifts ($0.7 \lesssim z < 2.5$), where powerful AGN significantly contribute. Although not conclusive, this is suggestive of a link between the process of SF and radio AGN activity (see also e.g. Boyle et al. 1998). This can be understood in the scenario of galaxy formation where gas-rich mergers of spiral galaxies lead to the formation of gas-poor elliptical galaxies. As the galaxies merge, the bulk of their cold gas, that was originally distributed throughout the disk of the merging constituents, is funneled into the inner few kpc of the merging system and fuels both star formation and AGN activity. Thus, a link between star forming and powerful radio AGN activity is predominantly expected in post-merger systems, consistent with the properties found in powerful radio AGN (see Smolčić et al. 2009b and references therein). On the other hand, the evolution of the integrated comoving 20 cm luminosity density for SF and radio AGN galaxies decouples below $z \sim 0.7$ where weak radio AGN start to dominate the total AGN radio-power output. In Smolčić et al. (2009b) we have shown that weak AGN are already at $z \sim 1$ hosted by the most massive galaxies ($< \log M_* >= 11.2$ $M_\odot$), and they are likely candidates for the 'radio mode' AGN feedback (e.g. Croton et al. 2006, Bower et al. 2006).

4. The Evolution of Radio AGN Feedback in Massive Galaxies

Correlating monochromatic 20 cm power to the kinetic power output (Birzan et al. 2008), we derive the mechanical energy injected into the surrounding medium by low-power (VLA-COSMOS) radio AGN ($\Omega_{\mathrm{L\,mech}}$; Smolčić et al. 2009b). The resulting evolution of $\Omega_{\mathrm{L\,mech}}$ is shown in Fig. 3 , where we compare it to the density of the radio mode heating given in the Croton et al. (2006) cosmological model (see their Fig. 3). Both the model- and observation-based heating rates are subject to large uncertainties. The model cooling rates are likely to be over-estimated by a factor of 2-3 (indicated in Fig. 3) due to the nature of the underlying cooling flow model (Best et al. 2006). On the other hand, the observationally derived heating rates have uncertainties of the order of $\sim$ 0.8 dex due to the scatter in the conversion of monochromatic to mechanical radio luminosities. Nonetheless, the qualitative agreement between the model and observations seen in Fig. 3 is encouraging for the idea that radio luminous AGN play an important role in the process of galaxy evolution.

Based on two samples of local massive red galaxies with available optical, radio and X-ray observations, Best et al. (2006) have shown that radio source activity may indeed control the growth rate of the host galaxy, as has been proposed in cosmological models. Best et al. have found that, across a wide range of stellar masses, the radio source heating rate agrees remarkably well with the cooling rate of the host galaxy's surrounding hot gas halo. Averaged over time, the recurring radio source activity can then balance the radiative losses from its surrounding hot gas halo and thereby suppress the cooling of the gas, and in this way control the growth rate of the galaxy. We have shown that various properties of $z \sim 1$ (low power) radio AGN are comparable to the properties of local radio AGN. Thus it is very likely that the same radio heating – hot gas cooling interplay, observed locally, takes place also in radio AGN at $z \sim 1$. This then strongly argues in favor of the plausibility that (low-power) radio AGN activity is a key parameter for preventing further stellar mass growth in massive 'red-and-dead' galaxies across cosmic times, at least since $\sim$ 4.5 Gyr after the Big Bang.

5. Summary and Conclusions

Using the largest samples of radio luminous star forming galaxies, and weak radio AGN at intermediate redshifts available to-date drawn from the VLA-COSMOS survey, we explored the evolution of the radio star forming and AGN

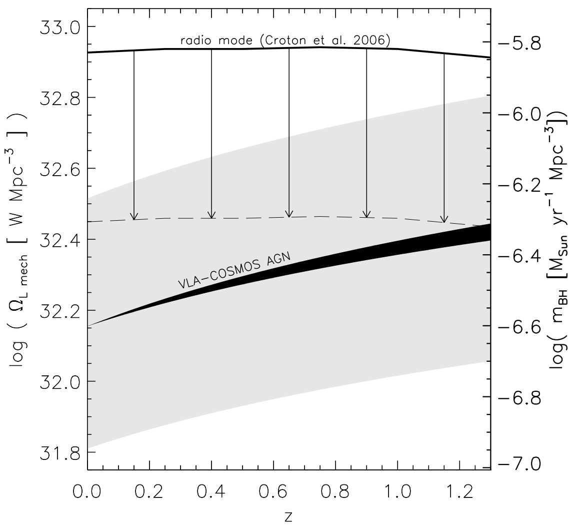

Figure 3. The cosmic evolution of the volume averaged mechanical heating rate $\Omega_{\rm L\,mech}$ for weak ($L_{\rm 1.4GHz} \lesssim 5 \times 10^{25}$ W Hz^{-1}; VLA-COSMOS) AGN, which are likely candidates for the 'radio mode' heating invoked in cosmological models (filled curve). The volume averaged accretion rate is shown on the right-hand side y-axis. The uncertainties in the correlation between $L_{\rm 1.4GHz}$ and $L_{\rm mech}$ are illustrated by the light-gray shaded area. Also shown is the evolution predicted in the Croton et al. (2006) semi-analytic model (thick line), and its possible value lowered by a factor of 2-3 (indicated by arrows) due to a systematic over-estimation of the heating rate in the model.

population out to a redshift of z∼1. Joint analysis of the evolution of the 20 cm luminosity density of the AGN and the star formation rate density suggests that the powerful radio sources are preferably triggered in major mergers following shortly after the phase of massive star formation at high redshifts. This would also naturally explain the strong decline of these sources below a redshift of z=1. As the volume density of weak radio AGN stays fairly constant, they can significantly contribute to the heating of the their surrounding medium and thus inhibit gas accretion onto their host galaxies as recently suggested for the 'radio mode' feedback in cosmological models.

References

Best, P. N., et al. 2006, MNRAS, 368, L67
Bower, R. G., et al. 2006, MNRAS, 370, 645
Boyle, B. J., et al. 1998, MNRAS, 293, L49
Birzan, L., et al. 2008, ApJ, 686, 859
Croton, D. J., et al. 2006, ApJ, 654, 858
Sadler, E. M., et al. 2002, MNRAS, 329, 227
Sanders, D. B., Mirabel, I. F., 1996, AR&AA, 34, 749
Schinnerer, E., et. al. 2007, ApJS, 172, 46
Scoville, N., et. al. 2007, ApJS, 172, 1
Smolcic, V., et al. 2006, MNRAS, 371, 121
Smolcic, V., et al. 2008, ApJS, 177, 14
Smolcic, V., et al. 2009a, ApJ, 690, 610
Smolcic, V., et al. 2009b, ApJ, accepted, arXiv:0901.3372
Willott, C. J, et al. MNRAS, 322, 536

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