

Chapter 7 Our Cosmic History: Continuum

Summary: Cosmic History: Continuum

Authors: Kristina Nyland (Naval Research Laboratory), on behalf of the SAC)

The formation and evolution of supermassive black holes (SMBHs) and galaxies are believed to proceed in a symbiotic manner, commonly referred to as SMBH-galaxy co-evolution. Although we have made great strides in understanding the co-evolution of SMBHs and galaxies over the past century, many important unsolved puzzles remain. In particular, a detailed understanding of the physical drivers of galaxy evolution, such as feedback from active galactic nuclei (AGN), is lacking. Major advancements in our understanding of SMBH-galaxy co-evolution ultimately require new and innovative approaches to tracing supermassive black hole and stellar growth over billions of years of cosmic history.

Historical challenges to surveying the faint populations of AGN and star-forming galaxies in an unbiased and statistical manner include insufficient sensitivity, obscuration effects, sky area coverage, and host galaxy cross-identification accuracy. The radio continuum surveys planned for the DSA-2000 will overcome each of these challenges and ultimately provide a complete and obscuration-free census of the formation and growth of SMBHs and the galaxies in which they reside. With its unprecedented combination of sensitivity and wide sky area coverage, the DSA-2000 will identify billions of radio continuum sources associated with AGN and star-forming galaxies in an obscuration-free manner. The DSA-2000's angular resolution of $3.5''$ will enable accurate host galaxy cross-identifications with new optical/NIR telescopes and surveys, including the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST), *Euclid*, and the *Nancy Grace Roman* Space Telescope. Furthermore, the multi-epoch + broadband spectral coverage of the DSA-2000 will distinguish between low-level AGN and star formation emission on the basis of slow radio variability and spectral shape.

Supermassive Black Hole Seeds: The DSA-2000 will identify >100 million AGN, providing a large statistical database for exploring SMBH formation and growth. With a sensitivity of 500 nJy/beam over $30,000$ deg² for the shallowest/widest survey planned, the DSA-2000 will reveal previously “hidden” populations of AGN at high redshift, low-mass, and low-luminosity that have yet to be fully explored. In the low-mass SMBH regime, the DSA-2000 will constrain SMBH seed formation models. Improved observational constraints on SMBH formation are especially timely and important given NANOGrav's recent detection of a low-frequency gravitational wave background that is consistent with SMBH inspirals.

AGN Jet Physics: Radio spectral modeling may be used to measure the evolutionary stage and physical conditions of compact AGN jets. The DSA-2000 will provide broadband radio light curves covering 16 epochs that will enable direct measurements of AGN jet duty cycles and lifetimes. Comparison with multiwavelength spectroscopic surveys will provide further insights into radio AGN jet triggering (e.g. whether a recent galaxy merger commonly precedes the formation of a jet). The DSA-2000's radio continuum census of AGN from $z = 0$ to the epoch of reionization will further constrain the importance of jet-driven feedback for shaping galaxy evolution. At lower redshifts ($z < 1$), the DSA-2000 continuum data may also be combined with spectral line measurements of HI to identify and study the physical properties (mass, velocity, etc.) of jet-driven outflows.

Star-forming Galaxies: The DSA-2000 will survey the μ Jy radio continuum source population dominated by star-forming galaxies in unprecedented detail. The DSA-2000 is expected to identify several hundred million star-forming galaxies. Contamination from faint, but variable, AGN will be mitigated using the multi-epoch radio light curve data. The DSA-2000 will therefore enable unbiased statistical analyses of the unobscured cosmic star formation rate density (SFRD) as a function of redshift. The SFRD encodes important information on the timing of stellar mass assembly in different types of galaxies and environments, and is therefore of fundamental importance for understanding the connection between SMBH and galaxy growth over cosmic time.

7.1 The Case for a Deep Wide-Area Continuum Survey

Authors: Tessa Vernstrom

Summary

There are a number of science drivers for a wide-area deep continuum survey. These range from Galactic, galaxies (both star-forming and AGN), large-scale structure and cosmology. Such a deep Northern survey would be an important compliment to the Southern surveys of the SKA, as well as Northern low-frequency surveys such as though with the LOFAR telescope.

State of the Field

While there are many sciences case that could be discussed I highlight two major ones here.

- **AGN:** With good surface brightness sensitivity, extended emission from radio galaxies will be detected that will change our understanding of their overall structure (see Bruggen et al. 2021; Norris et al. 2021b, for examples from EMU pilot survey). This will influence models of the powering jets as well as the interactions with the surrounding medium. In addition, strange structures which challenge our models are important but rare, and can only be found by surveying sufficiently large areas of sky with superb surface brightness sensitivity. Giant radio galaxies are probes of both extreme jet physics and low density environments, and still present a quandary - are they an evolutionary state of AGN or a product of environment ? To answer this a large sample of GRGs are needed. Dying radio galaxies, or remnants, are important for understanding the duty cycle of AGN and, when relaxed, are a good probe of surrounding pressures. A key question is where the radio emission of high-redshift infrared-luminous sources arises, i.e., a weak jet, quasar winds, disk winds, nuclear starburst, or something else. Because of the relatively low radio luminosity of the majority of these high-z sources highly sensitive observations are needed.
- **Cosmology:** Large radio surveys have the capability to provide important tests of the fundamental physics of the Universe, including questions such as the nature of the accelerating force (Dark Energy) and the mechanism that generates the initial conditions, both of which are currently mysteries. Radio galaxies can be used to trace the distribution and the evolution of the gravitational potential at higher redshifts through their clustering statistics. By cross-correlating radio surveys with the CMB the late-time Integrated Sachs-Wolfe (ISW) effect (Crittenden & Turok 1996; Stolzner et al. 2018) can be measured. This cross-correlation also enables the characterization of the redshift distributions and bias of the radio source population (Alonso et al. 2021), but requires a large contiguous area and high source density to be uniformly sampled. Cross-correlating with a galaxy survey (e.g., WISE, VHS, DES, KiDS, DESI Legacy) further allows cosmic magnification (Scranton et al. 2005) to be detected and utilized. This is in addition to studying the large-scale clustering of the faint radio source population, weak lensing, as well as searches for dipoles and tests of non-Gaussianity.

DSA-2000's impact

All of the cosmological tests require a large sample of galaxies over the whole sky, as their precision scales with the area covered and the number density of sources. Of these, area is more vital, and a maximal area is the best case (thus the area covered by DSA-2000 and or DSA-2000 combined with SKA). Reducing the area has an effect that is greater than just a linear scaling, as with other science cases. Poorer resolution and sensitivity lowers the effective source count, and makes splitting the sample

into multiple redshift bins less effective (see Asorey & Parkinson 2021).

Regarding remnant galaxies, as well as diffuse cluster emission, the low frequency array, LOFAR, and its LoTSS survey have found many interesting objects but a higher frequency survey, well-matched in sensitivity to LOFAR, is needed to increase detections as well as spectrally confirm the types of objects that have been found (or spectrally confirm the particle acceleration mechanisms at play).

The DSA-2000's sensitivity will probe AGN in the highest numbers out to the highest redshifts. This will enable study of AGN evolution across cosmic times better than any previous survey.

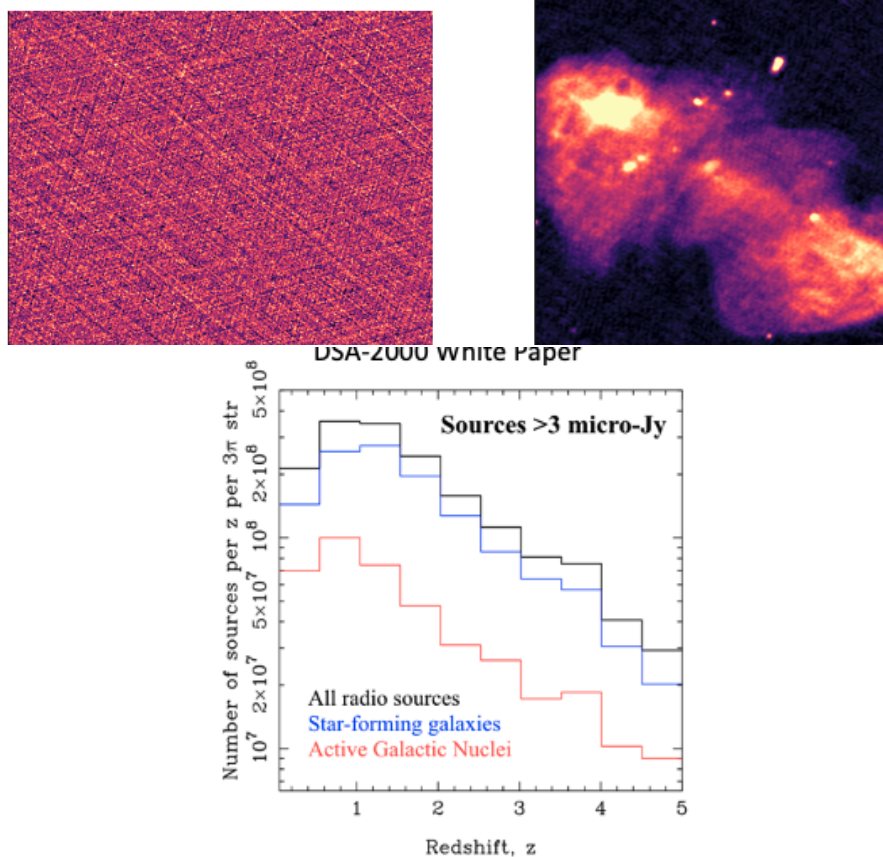


Figure 7.1: Top: shows a comparison of a giant radio galaxy of the new VLA Sky Survey data with that of LOFAR LoTSS. Demonstrating the need for a deep higher frequency survey that is well-matched in LoTSS in sensitivity and surface brightness sensitivity. Bottom: From the DSA-2000 white paper, showing the large number of high-redshift AGN that would be detected by the DSA-2000.

System requirements / desired additions to baseline design

N/A

7.2 A clean history of star formation over cosmic time

Authors: Allison Matthews (Carnegie Observatories)

Summary

The DSA-2000 will detect a billion individual radio sources down to $3.5 \mu\text{Jy}$ and constrain the radio population as a whole down to 15 nJy —flux density levels necessary for detecting radio emission from star formation in the first few Gyr of cosmic time. Since radio emission is a dust-unbiased tracer of star formation rate, the DSA-2000 all-sky and deep surveys will provide a truly clean and robust history of star formation throughout cosmic history.

State of the Field

Our understanding of SFRD evolution has been primarily driven by ultraviolet (UV), optical, and infrared (IR) observations, which are shrouded in uncertainties due to dust and the presence of older stellar populations. Getting around the dust is key to getting the science right. Radio observations have the distinct advantage of being entirely unaffected by dust and old stars. Cosmic ray electrons accelerated in the supernova remnants of massive stars produce the radio synchrotron emission associated with star-forming galaxies (SFGs). The legitimacy of radio emission as an SFR indicator rests on the tight, empirically determined FIR/radio correlation (Helou, Soifer, and Rowan-Robinson 1985; Condon, Anderson, and Helou 1991). However, radio observations are not without their own uncertainties. AGN can also contribute to radio emission, and ordinary SFGs are very faint at radio frequencies. Our Milky Way would have a flux density of only $S_{1.4 \text{ GHz}} \sim 1 \mu\text{Jy}$ at $z \sim 2$, the peak of star formation (cosmic noon).

Recent upgrades to the VLA and the coming online of “next generation” interferometers (e.g. MeerKAT) have enabled radio observations deep enough to detect star-forming galaxies at high redshift (see Figure 1). Initial studies of the faint radio population ($S_{1.4 \text{ GHz}} < 100 \mu\text{Jy}$) indicate that the vast majority of radio sources in this flux density regime are powered by star-formation—not by AGN (Vernstrom et al. 2016; Algera et al. 2020; see Figure 1). The most sensitive 1.4 GHz image to date was taken when commissioning the MeerKAT telescope (Mauch et al. 2020). By analyzing the statistics of the confusion (overlapping faint sources) in this image, Matthews et al. 2021b constrained the radio source count down to $S \sim 0.25 \mu\text{Jy}$, the necessary flux level to detect Milky-Way like galaxies beyond cosmic noon. Brightness-weighted source counts at a given redshift are proportional to the the local luminosity function modified by luminosity and density evolution. When modeling the evolution of radio sources with redshift, Matthews et al. 2021a found that the counts demand that there is $\sim 50\%$ more star formation at nearly all epochs than implied by the prevailing UV/IR picture.

DSA-2000’s impact

The DSA-2000 will reliably detect a $\sim$ billion individual radio sources down to $3.5 \mu\text{Jy}$, even considering the effects of confusion. Unlike surveys done with higher angular resolution ($\theta < 1''$), the DSA-2000 will not have to correct for resolved sources missing because they have peak flux densities below the survey limit, but integrated flux densities above that limit. These corrections have led to excessive scatter among various faint source counts that cannot be attributed to Poisson counting error or galaxy clustering alone. The DSA-2000’s large statistical sample covering a generous swath of the sky with medium angular resolution will enable direct source counts down to faint flux densities with unprecedented precision and accuracy. The implications of such a large, reliable, and complete radio sample for the study of galaxy

evolution and cosmology cannot be limited to one paragraph. But for the purpose of this science case alone, the DSA-2000 will yield the first truly clean and robust measurement of the star formation history of the universe—free from uncertainties due to dust and cosmic variance.

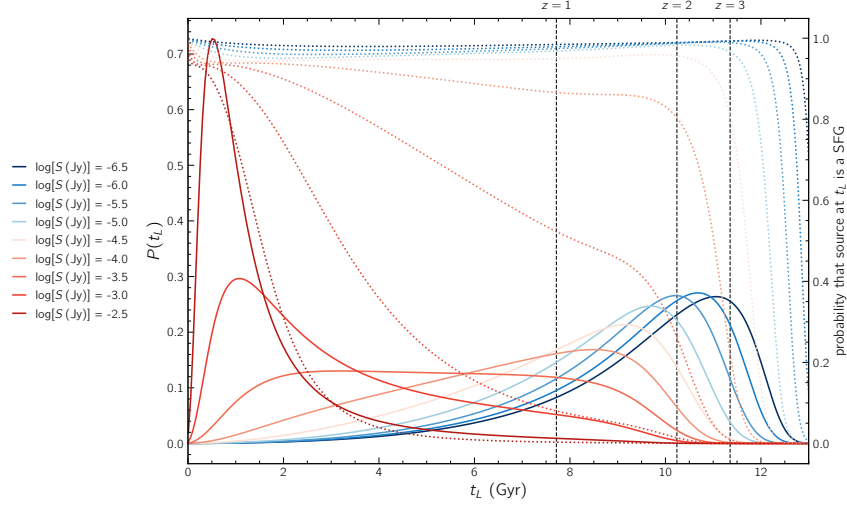


Figure 7.2: Solid lines: Lookback time t_L probability density functions of star-forming galaxies within bins of 1.3 GHz flux density with width 0.5 dex centered on $\log[S_{1.3\text{GHz}} (\mu\text{Jy})] = -6.5, -6, \dots, -2.5$. Dotted lines: Percentage of radio sources powered by star formation as a function of lookback time t_L within the same 1.3 GHz flux density bins of width 0.5 dex.

System requirements / desired additions to baseline design (see table below)

The DSA-2000 is (almost) perfectly suited for point-source continuum science. Assuming a reliable detection requires 25 beam solid angles per source, the angular resolution of $3.5''$ translates to a limiting source flux density of $\sim 3.5 \mu\text{Jy}$ for a blind radio survey. However, a DSA-2000 nearly-perfect Gaussian beam with minimal sidelobes ($< 1\%$) is particularly well-suited for analyzing the confusion statistics of deep images. A $P(D)$ analysis could constrain the evolution of radio sources down to $\sim 15 \text{ nJy}$.

7.3 New Insights on Quasar Jet Life Cycles with the DSA-2000

Authors: Kristina Nyland (Naval Research Laboratory)

Summary

The DSA-2000 will identify > 100 million active galactic nuclei (AGN). With its multi-epoch, broadband monitoring approach, the DSA-2000 will provide new insights into the physics of AGN feedback in the context of galaxy evolution. Its sensitivity will also reveal previously “hidden” populations of AGN at high redshift, low-mass, and low-luminosity that have yet to be fully explored.

State of the Field

The large-scale (10’s to 1000’s of kpc) lobes of radio galaxies and quasars regulate star formation (SF) via the inhibition of cooling flows in the intracluster medium (Fabian 2012). This mode of feedback is prevalent among massive galaxies in dense environments at low redshifts. However, classical radio galaxies and quasars represent a small minority ($\sim 1 - 10\%$) of all active galactic nuclei (AGN). Recent studies suggest that compact ($\lesssim 1$ kpc) jets may be common, perhaps outnumbering classical large-scale sources at cosmic noon ($z = 1 - 3$; e.g. Czerny et al. 2009). Compact jets may be associated with youth, lower intrinsic jet powers, interaction with a dense ISM, or shorter jet lifetimes (Jarvis et al. 2019, Patil et al. 2020, Nyland et al. 2020). Despite their prevalence, the potential impact and importance of feedback by compact jets with sub-galactic sizes, such as jets that are young or confined by a dense ISM, remains unknown.

Progress in this area requires deep, multi-epoch, broadband radio continuum data to track the evolution of growing quasar jets. A game-changing advancement in the search for young jets has recently been made possible by the Very Large Array (VLA) Sky Survey (VLASS; Lacy et al. 2020). VLASS is a multi-epoch (3 epochs over 7 years) survey at 2–4 GHz of the entire northern sky visible to the VLA ($\delta > -40^\circ$). Candidate newborn quasar jets have been identified by comparing recent data from VLASS and historical radio surveys, such as the Faint Images of the Radio Sky at Twenty Centimeters (FIRST; Becker et al. 1995) taken from 1993–2011. Nyland et al. (2020) identified a sample of 26 quasars with jets that have brightened dramatically in the radio in the past 1–2 decades by comparing FIRST and VLASS. The radio properties are consistent with young, pc-scale jets (e.g., GPS sources; O’dea & Saikia 2021) launched in the past few decades, possibly associated with a state transition of the SMBH, making them among the youngest jets known (Gugliucci et al. 2005). As VLASS and other on-going multi-epoch radio continuum surveys, such as VAST (Murphy et al. 2021), continue, additional candidate newborn quasar jets are expected to be identified.

DSA-2000’s impact

The sensitivity, resolution, and time domain coverage of the DSA-2000 will enable fundamental new advancements in our understanding of jetted AGN and quasars. In particular, the multi-epoch + broadband spectral coverage of the DSA-2000 will identify young and growing jets on the basis of their slow radio variability (over timescales of years) and radio spectral modeling (Figure 1). This will enable direct measurements of quasar jet duty cycles and lifetimes for statistical samples of newborn quasar jets. Together with multiwavelength data from other instruments/surveys that are expected to be operating in the 2020’s (e.g. Roman, Euclid, LSST), the DSA-2000 will allow us to explore how quasar jets influence (and are influenced by) their environments over cosmic time.

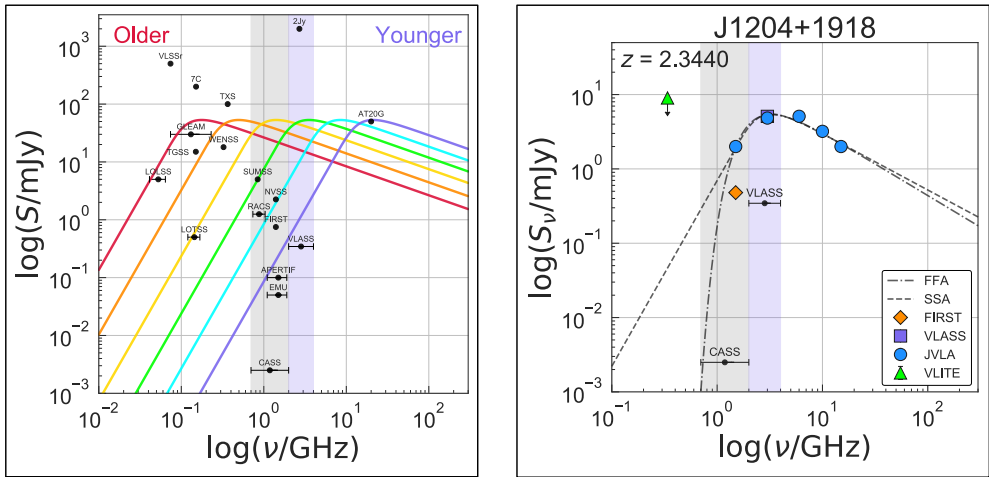


Figure 7.3: Examples of radio continuum spectra of peaked spectrum sources. The frequency ranges of the DSA-2000’s CASS and VLASS are shaded in gray and blue, respectively. **Left:** Radio survey sensitivity ($5\sigma_{\text{rms}}$) vs. frequency. Representative synchrotron self absorption curves with turnover frequencies that increase from 125 MHz (red) to 15 GHz (blue). As a young radio source expands and gets older, the turnover frequency shifts from high to low frequencies. Different radio surveys thus preferentially select radio AGN in different life stages. **Right:** Example radio spectrum of a quasar with a newborn jet discovered in the slow radio time domain from (Nyland et al. 2020). The CASS will have sufficient sub-GHz sensitivity to determine the origin of the absorption (e.g. synchrotron self absorption vs. free-free absorption) in peaked-spectrum AGN.

System requirements / desired additions to baseline design (see table below)

N/A

Table 7.1: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Spatial resolution	3.5"	✓ sufficient for quasar-host matching
polarization	IQUV for 2 MHz channels, I only for all other channels	✓ “bonus” quasar science
low-resolution HI channels	5600 channels from 0.7–1.45 GHz, 134 kHz (28 km s ^{−1} at z=0, 56 km s ^{−1} at z=1)	✓ sufficient for quasar outflows
Cadence	1 every 4 months	✓ quick data release turnaround preferred
need for additional modes	N/A	long-baseline outriggers (< 1'' imaging)?

7.4 Where do stars explode? – A comprehensive volume-limited census of atomic gas around supernovae and their progenitors with DSA-2000

Authors: Sumit K. Sarbadhicary (OSU), Adam Leroy (OSU), Eric Koch (CfA), Ness Mayker Chen (OSU), Erik Rosolowsky (U.Alberta), Jordan Wagner (OSU), LGLBS + PHANGS teams

Summary

With DSA-2000, we will obtain the largest sample of “supernova ISM densities” – average density of the ambient gas environments where stars inject their explosion energy. The ambient density plays a major role in the proportion of thermal vs momentum feedback from supernovae, which in turn sets the global star-formation properties of a galaxy at any given point in time. DSA-2000 will provide a much-needed observational census of such densities through simultaneous maps of 21 cm-traced atomic hydrogen and sites of stellar feedback (HII regions and supernova remnants) traced by 0.7-2 GHz radio-continuum for more than 10^4 galaxies in the 50 Mpc volume. The resulting measurement will serve as an indispensable benchmark for design and calibration of feedback models, which are currently the largest sources of uncertainties in galaxy simulations.

State of the Field

Stellar feedback, particularly in the form of supernovae (SNe), is an important regulator of the star-formation history of galaxies. Supernovae inject heat and momentum into the ISM, which drives powerful outflows that disperse gas and cycle metals through the ISM and CGM, produce ISM turbulence, amplify magnetic fields and accelerate cosmic rays that provide pressure support in the ISM, and maintain a multi-phase ISM distribution. The non-linear interplay of these phenomena set the global star-forming properties of the galaxy at any given point of its evolution.

The outcome of SN feedback however depends sensitively on the ISM density, and it is unclear *apriori* the range of densities where stars typically explode as a result of the complex interplay of progenitor lifetimes, molecular cloud lifetimes, and stellar kinematics. In dense molecular-cloud environments, SN energy gets quickly radiated away, while in low-density environments, energy is more efficiently retained. The locations in the ISM where SNe explode can therefore dramatically affect the distribution and filling factor of hot and cold gas, and eventually star-formation and outflow rates. An understanding of the distribution of ambient gas densities of SNe is therefore critical for the design and calibration of subgrid models of feedback, which remain the largest source of uncertainty in modern cosmological simulations of galaxy formation.

Recently, ALMA and JVLA has opened the window to sensitive imaging of the 21-cm atomic and CO-traced molecular gas down to individual cloud scales in nearby galaxies, making it possible for the first time to also probe the ‘local’ ISM environments of actual SN explosions. With the PHANGS survey of molecular ISM in nearby star-forming galaxies within 20 Mpc, Mayker Chen+ (2023) found that core-collapse SNe (Type II and Ib/c) are more likely to explode near giant molecular clouds than SN Ia, but nearly 60% of core-collapse still explode in regions of no detectable H_2 . In Sarbadhicary+ (2023, in prep), where we had access to both *atomic* and molecular gas maps of M33 (thus fully accounting for the mass-filling ISM phase), we showed that younger massive stars are more likely to explode in dense molecular-dominated environment, but a significant (>44%) of even these youngest ($> 20 M_\odot$) stars (whose lifetimes are comparable to typical clouds) explode in the atomic-gas-dominated inter-cloud medium, likely due to pre-SN feedback clearing the parent molecular cloud of their OB associations, and some contribution from kicks from stellar interaction that deserves continued

investigation (Figure 1).

While these results show the value of targeted surveys of nearby SN galaxies for such studies, an all-sky high-resolution survey like DSA-2000 will be a major leap by providing an orthogonal ‘large survey’ counterpart to this line of work as we explain below.

DSA-2000’s impact

With DSA-2000, we will have 21-cm spatially-resolved atomic gas observations of over 15000 LMC-like-and-larger galaxies out to 50 Mpc, at an unprecedented resolution of $3.5''$, enabling both cloud-scale studies (at spatial resolution of <100 pc) of SN gas environments for galaxies within 5 Mpc, and the kpc-scale environments for an even larger sample of SNe out to 50 Mpc. Within this 50 Mpc volume, current discovery statistics indicate a sample of over 300 known historical SNe (Cronin+ 2021), and an expected 50-100 future core-collapse SNe per year with Rubin-era surveys. This statistical information of SN gas environments at different spatial resolutions will be a unique and novel guide for theoretical simulations that are also carried out with different grid-resolution elements (depending on the simulated density/volume), allowing them to more closely align their input feedback physics with observations and accurately predict properties from first principles.

The simultaneous radio-continuum observations will also provide an unprecedented sample of the HII region and supernova remnant (SNR) population in these galaxies, free from extinction-related uncertainties, in the $z \sim 0$ universe. HII regions will provide a census of the massive young stellar objects/OB-associations where significant pre-SN feedback (i.e. winds, radiation-pressure, photoionization) is taking place, while SNRs, particularly within 10 Mpc, will provide an additional 10-100 ‘past’ SN explosions per galaxy.

System requirements / desired additions to baseline design

Specifications are well-optimized for the proposed science. Higher angular resolution and wider bandwidths (e.g. up to S-band), if possible, would be useful for localizing targets and obtaining higher S/N spectral index measurements (for classifying continuum sources) respectively.

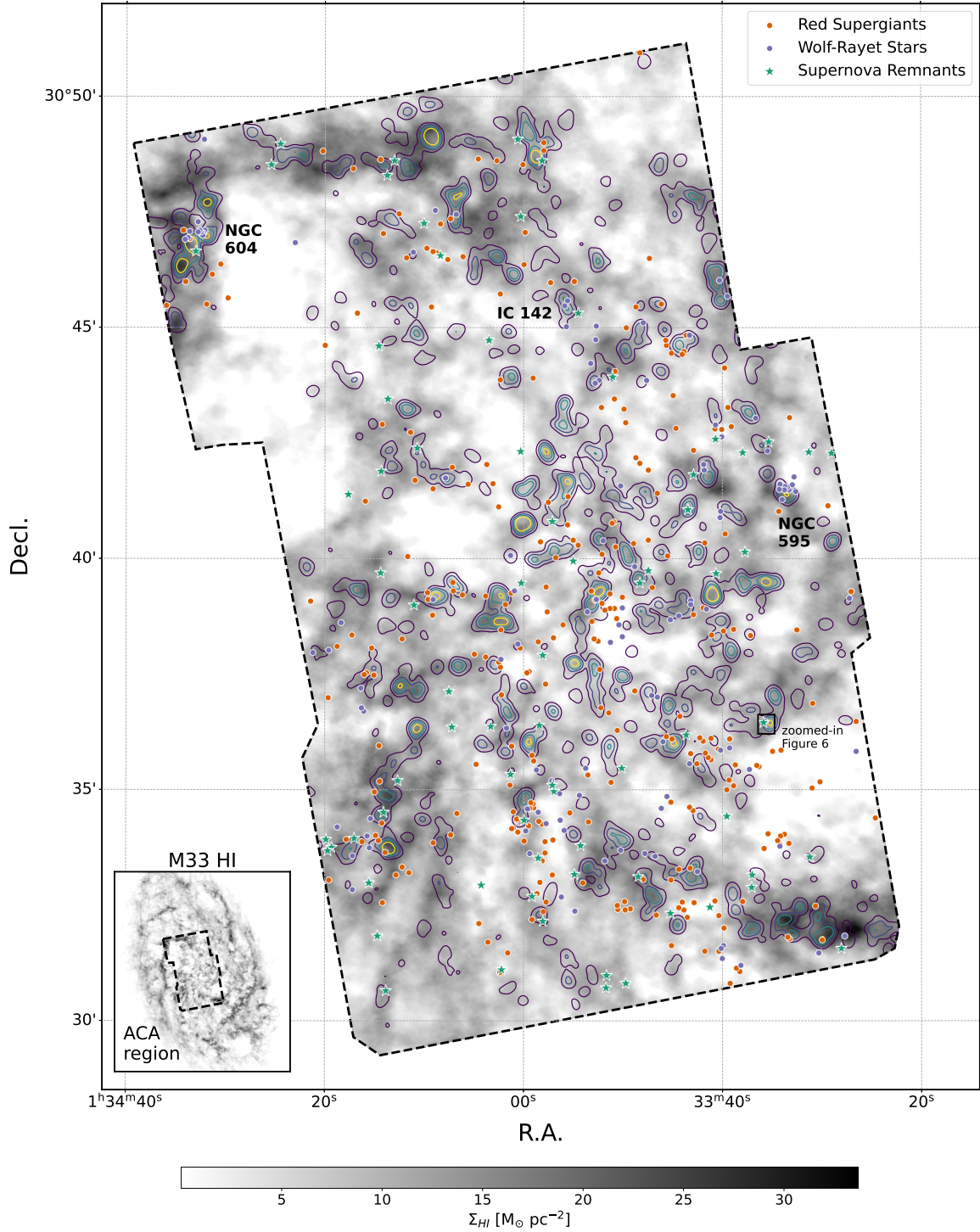


Figure 7.4: The spatial distribution of red-supergiants (RSGs), Wolf-Rayet stars (WRs) and supernova remnants (SNRs) with respect to the cold ($H_2 + HI$) ISM in the M33 ACA survey region (Sarbadhicary+ 2023, in prep). These stars will explode in future as core-collapse SNe and our 21 cm survey provides the ambient density distribution in which they will deposit their energy. Extending this to a large sample at a variety of spatial resolution elements will paint a complete observational picture of where stars inject energy in the ISM to guide the next generation of cosmological simulations.

7.5 Constraining models of cosmic-ray transport in L-star galaxies with DSA-2000

Authors: Sam Ponnada

Summary

The physics of highly relativistic charged particles, cosmic rays (CRs), have recently been included in simulations of galaxy formation. With a variety of physical and numerical treatments, these simulations have shown that CRs may play an important role in galaxy formation and evolution, contributing a significant source of non-thermal pressure support in the circum-galactic medium (CGM) with corresponding effects on the CGM gas phase structure and transport of cool gas from the inter-galactic medium (IGM) to the disk. However, these notable effects in the CGM are dependent on the macroscopic transport rate of CRs, which are highly dependent on micro-physical, plasma-scale physics of CRs, for which there is large model variation. Current observational constraints are very limited at delineating between models of CR transport, and so novel constraints are needed. By increasing our sample of spatially resolved non-thermal emission from galaxies by orders of magnitude, DSA-2000 will provide crucial new constraints on CR transport in galaxies in both the ISM and CGM.

State of the Field

Highly relativistic charged particles (cosmic rays) and magnetic fields (**B**) have recently been included in simulations of galaxy formation Booth et al. 2013; Marinacci, Pakmor, and Springel 2014; Butsky and Quinn 2018; Hopkins et al. 2020; Buck et al. 2020). Injected by dying stars into the interstellar medium (ISM), CRs have long known to be an important source of non-thermal pressure in the ISM (Boulares and Cox 1990) and have notable dynamical and chemical effects as they traverse along magnetic field lines throughout the ISM and into the circum-galactic medium (CGM). The recent simulations of galaxy formation have predicted considerable dynamical effects of the 1-10 GeV CRs (which dominate the bolometric CR energy density) in the CGM of L_* galaxies - CRs have been shown to be capable of establishing significant non-thermal pressure in the halo, acting as a source of significant preventative feedback by preventing cool gas inflow to the ISM and changing the phase structure of the CGM.

While these physical effects of CRs have been noted in galaxy formation simulations with highly variant physical and numerical treatments, the macroscopic effects of CRs ultimately depends on the physics of their transport on "microscopic" plasma scales, where the dominant scattering mechanisms of CRs remain deeply uncertain Hopkins et al. 2021a; Hopkins et al. 2022. Two popular model classes proposed in the literature are those of "extrinsic turbulence" and "self-confinement", where CRs scatter off of gyro-resonant fluctuations in **B** following some turbulent cascade in the fluid, and where CRs excite these gyro-resonant fluctuations as Alfvén waves themselves via streaming instabilities and subsequently scatter (Jokipii 1966; Skilling 1975). While these model classes predict qualitatively quite different scalings of the CR scattering rate as a function of plasma properties like gas density, strength of **B**, ionization fraction, temperature, etc., there are model variants within these model classes remain in agreement with the existing constraints we have on CRs from Voyager and Fermi-LAT (Hopkins et al. 2021b).

To make further progress in this field, new observational constraints are required to determine the dominant mode of CR transport in galaxies and subsequently their effects on galaxy formation and evolution. Towards this end, we have produced synthetic synchrotron images from high-resolution, cosmological, magneto-

hydrodynamic simulations of galaxy formation from the Feedback in Realistic Environments project (FIRE-2; Hopkins et al. 2020; Hopkins et al. 2021b; Ponnada et al. 2022) which evolve CRs using different models of CR transport described above. Preliminary results indicate that deep radio surveys sensitive to the low-surface brightness emission from galaxies will be able to provide very crucial constraints on the dominant mode of CR transport in galaxies.

DSA-2000's impact

The DSA-2000 will measure low-surface brightness, non-thermal emission from 10^5 face-on and edge-on L_* galaxies, which will provide crucial constraints on CR transport physics both in the ISM and in the inner CGM, where there are few extra-galactic constraints.

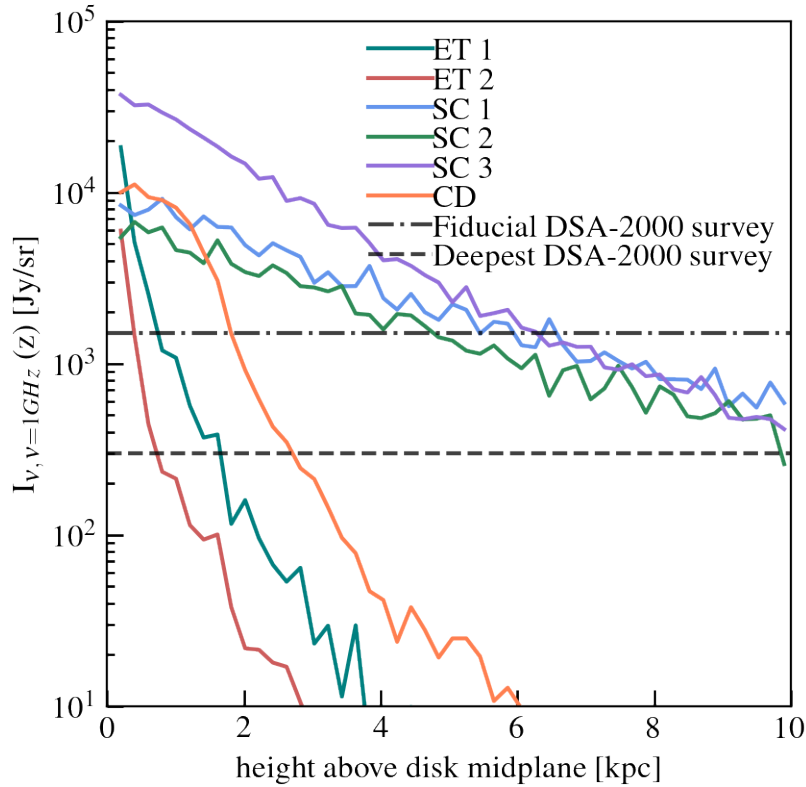


Figure 7.5: Vertical specific intensity profiles at 1 GHz ($I_{\nu, \nu=1\text{GHz}}(z)$) for a FIRE-2 L_* galaxy run with various cosmic-ray transport models. The DSA-2000 will be able to detect diffuse, low-surface brightness emission offset by a few kpc from the mid-plane of the disks of $\sim 10^5$ galaxies out to 200 Mpc, providing crucial constraints on cosmic-ray transport in the inner CGM of galaxies.

Note: could use a check on the fiducial/deep DSA-2000 lines quoted here, assumed beam of 3.5'', 500 and 100 nJy/beam respectively

System requirements / desired additions to baseline design

N/A

7.6 Compact Symmetric Objects: The Possible Connection with Tidal Disruption Events

Authors: A. C. S. Readhead, V. Ravi, I. Liodakis, M. Lister, S. Kiehlmann, and P. N. Wilkinson

Summary

Compact Symmetric Objects (CSOs) are compact (< 1 kpc), jetted-active galactic nuclei (AGN), in which the observed emission is NOT strongly beamed towards the observer, as is the case with blazars and most other high-luminosity compact jetted-AGN. The class was introduced in order to identify a class of jetted-AGN in which the absence of strongly beamed emission towards the observer makes it possible to make accurate determinations of the physical properties of the emission regions, such as the magnetic field strength, the particle energy density, the speed of components moving along the jets, and the speed of advance of the jets through the interstellar medium. These physical quantities are difficult to determine in blazars due to the uncertainties introduced by relativistic beaming. Unfortunately, the main purpose of the classification, which was to discriminate between objects whose observed emission is strongly beamed towards the observer, and those in which it is not, was not understood by many in the astrophysics community, who interpreted the CSO classification merely as a purely morphological classification, and as a result the class has been contaminated by blazars mis-classified as CSOs. This has now been rectified by the introduction of a set of stricter criteria for inclusion in the CSO class. Two major classes of CSOs have been identified: a low-luminosity, edge-dimmed class (CSO 1), and a high-luminosity, edge-brightened class (CSO 2). A recent study of 79 bona fide CSOs has revealed that CSO 2s provide a unique time domain window on central engines of AGN and the supermassive black holes (SMBHs) that drive them, since they are (i) a distinct class of jetted-AGN with a sharp size cutoff at ~ 500 pc; (ii) the vast majority must be created in a manner different to other jetted-AGN; and (iii) that they might be caused by single star capture and hence provide an important link with Tidal Disruption Events (TDEs). Whatever their origin, it is clear that the systematic study of CSO 2s will be both crucial and pivotal for investigations of the launching of high-luminosity relativistic jets. The DSA-2000 is the ideal search engine for CSO 2s in view of its sensitivity, frequency coverage, polarization capability, and cadence.

State of the Field

To provide context, we begin with the emerging picture of the Compact Symmetric Object (CSO) Family, which is shown in Fig. 7.6. As we see, the CSO family is complex. This field has proven to be far richer than any of us at first imagined it would be, and it raises a number of crucial astrophysical questions that are listed at the end of this document.

The class of CSOs was defined by Wilkinson et al. 1994 in order to differentiate between the vast majority of compact radio sources observed in cm wavelength radio surveys, which are blazars with an asymmetric “core-jet” morphology, and the small number ($\sim 7\%$ in complete samples) of symmetric objects in which the observed emission is not strongly beamed toward the observer. Since the observed emission in CSOs is predominantly unbeamed, the magnetic field strengths, particle energy densities, and total energies may easily be determined, and hence compared with these properties in larger radio sources, FR Is and FR IIs (Fanaroff and Riley 1974). Another crucial property of CSOs is that they are compact enough to measure the separation speeds of their outer hot spots on timescales of years to decades, making them accessible to direct prediction

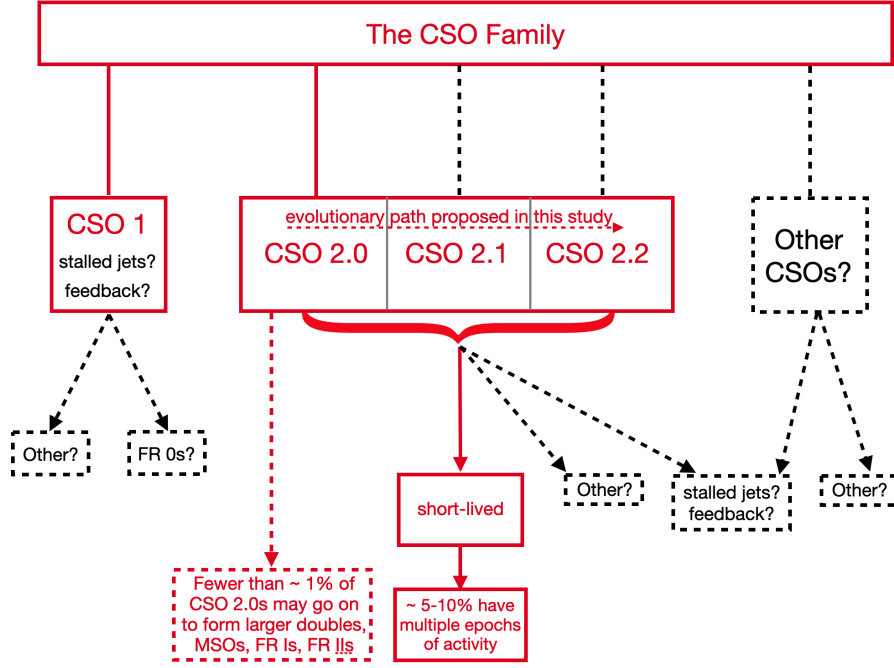


Figure 7.6: The emerging picture of the CSO Family thus far, from Readhead et al. 2023. The solid lines and arrows indicate distinctions that in our view have been firmly established in Kiehlmann et al. 2023b; Kiehlmann et al. 2023a; Readhead et al. 2023. The dotted lines indicate hypotheses that remain to be proven. The red items are all discussed in varying amounts of detail in the above three papers. The black items are other possibilities that have been discussed in the literature, and/or that are likely to be verified or discovered as we observe fainter CSOs and dig deeper into the CSO luminosity function.

and verification. In other words, CSOs open the window on time domain studies of $1000\times$ smaller analogs of FR I and/or FR II objects. Contamination of the CSO class by blazars has obfuscated their importance to studies of the central engines of AGN, and the mechanism(s) for launching relativistic jets. This has greatly hindered progress in the field. However, the criteria for inclusion in the CSO class have recently been strengthened and, following a comprehensive literature survey, a sample of 79 bona fide CSOs has now been defined by Kiehlmann et al. 2023b.

While this study was undertaken for the sole purpose of initiating the compilation of a comprehensive list of bona fide CSOs, it was confirmed during the course of the work that CSO 2s show an upper cutoff in size at around 500 pc, as can be seen in Fig. 7.7, i.e. well before the nominal cutoff at 1 kpc imposed by the compact selection criterion (Kiehlmann et al. 2023a). Statistical tests of the size cutoff were carried out using the three complete samples of Pearson-Readhead, Caltech-Jodrell 1, and the Peacock and Wall (Pearson and Readhead 1988; Polatidis et al. 1995; Peacock and Wall 1981; Peacock and Wall 1982; Wall and Peacock 1985). Although these numbers are small, the Kolmogorov-Smirnov test shows that the cutoff is significant at the 3.6σ (p-value 1.6×10^{-4}) level, and the binomial test returns almost identical results. This in itself is a robust statistic that makes for a compelling case for an upper cutoff in size at ~ 500 pc, and age at ~ 5000 yr. In addition, the fractions of CSO 2s relative to FR Is and FR IIs in complete samples, and the redshift distribution of CSO 2s in complete samples both provide completely independent strong corroborative evidence that CSO 2s constitute a population of jetted-AGN that is distinct from the other classes of jetted-AGN, including compact steep spectrum(CSS) objects, medium symmetric objects (MSOs), FR Is and FR IIs, and must therefore have a significantly different physical origin than these other classes. *Simple intermittent fueling, for example, cannot cause a sharp cutoff in the distribution in physical sizes such as that seen in Fig. 7.7. There must be an upper*

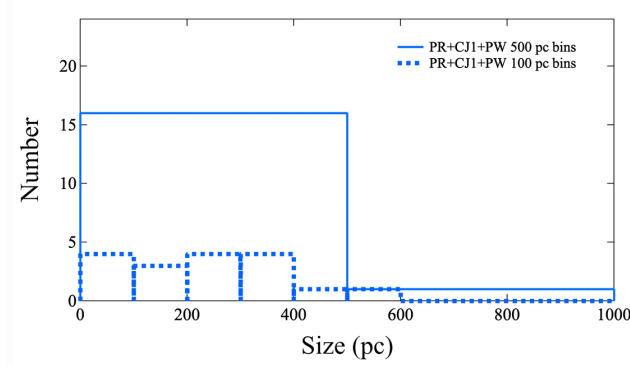


Figure 7.7: Distribution of physical sizes of the CSO 2s from Kiehlmann et al. 2023b in the complete PR+CJ1+PW samples, showing a sharp cutoff at ~ 500 pc.

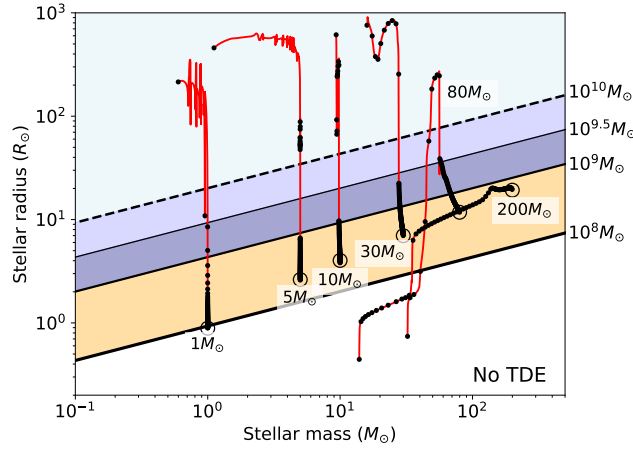


Figure 7.8: Regions in the stellar radius-mass space where disruption is possible outside the event horizons of SMBHs of different masses, from Readhead et al. 2023. The lower limits, corresponding to $R_T/R_S = 1$ for SMBHs of various masses as labeled, are shown as lines, and the shaded area indicates where disruption is observable. We also show evolutionary tracks for solar-metallicity stars of $1M_\odot$, $5M_\odot$, $10M_\odot$, $30M_\odot$, $80M_\odot$, and $200M_\odot$ interpolated from the MESA Isochrones and Stellar Tracks (MIST). The stars are evolved from the zero-age main sequence (indicated as open circles) either to the end of thermal pulsations on the asymptotic giant branch, or to supernova. Each track is garnished with black dots that indicate intervals of $1/100$ of the lifetime of each star. For example, a $1M_\odot$ star can be disrupted by a $10^9M_\odot$ SMBH for $\sim 4/100$ of its lifetime.

limit to the fuel available, which is why we favor the single star capture hypothesis, where the initial mass function provides the kind of upper limit that is needed.

A study carried out by Readhead et al. 2023, of the 54 bona fide CSOs identified in Kiehlmann et al. 2023b, which have spectroscopic redshifts, shows that CSOs are differentiated by morphology in the luminosity-size (P, D) plane, in a way that is likely due to evolution. The distribution of CSO 2s in the (P, D) plane provides a powerful approach to questions of the variation of luminosity and the speed of advance of the jets with size and age in jetted-AGN. Studies of the energies required show that these are consistent with what might be supplied in the capture of a single star by a supermassive black hole in a galactic nucleus. The most luminous CSO 2s would require to be fueled by the capture of a massive star, and these have been found to spend enough time with their envelopes in the size range that can be disrupted by an SMBH, as can be seen in Fig. 7.8. Furthermore, the observed CSO 2 birthrates are consistent with those of jetted tidal disruption events (TDEs) (see Fig. 7.9).

Thus the known facts about CSO 2s are consistent with the hypothesis that most CSO 2s are formed by the capture of a single star by a quiescent SMBH in the nucleus of an elliptical galaxy. A very important

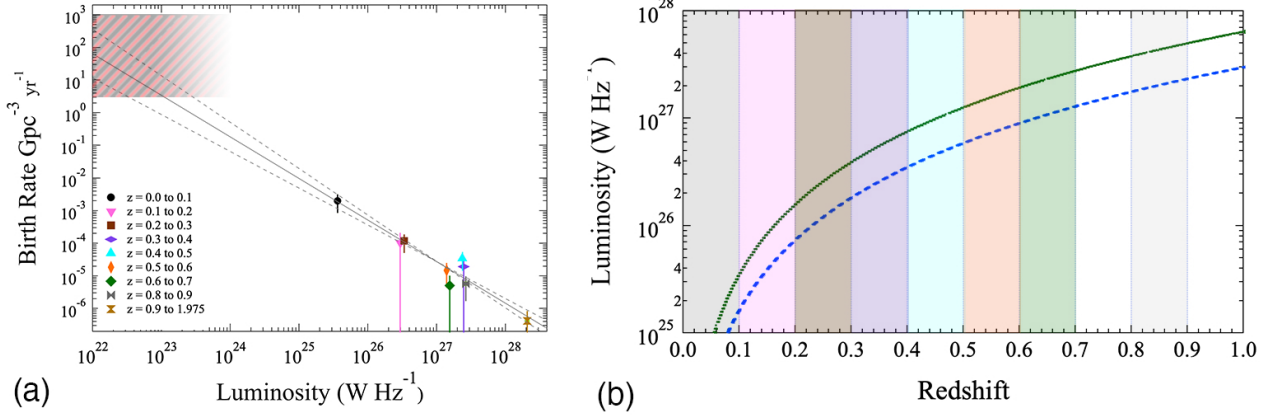


Figure 7.9: Dependence of birth rates of CSO 2s in the complete PR+CJ1+PW samples on luminosity, from Readhead et al. 2023. (a) The birth rates vs. luminosities of CSOs are shown by the plotted points. The solid gray line is the least squares fit to the points and the dashed lines show the $\pm 1\sigma$ ranges of the fit. The approximate range of birth rates for jetted TDEs is shown by the red and gray hatched region (see text). (b) the luminosity cutoffs of the PW (green line) and PR+CJ1 (blue dashed line) samples. The colors of the panels are faded versions of the colors in the different redshift ranges shown in (a).

scenario to be tested is that of a single star, tidally disrupted by an SMBH, providing magnetic field to the ergomagnetosphere, and the trapped magnetic flux providing the power to launch a Blandford-Znajek powered relativistic jet (Blandford and Znajek 1977). Were this scenario for extracting spin energy from the SMBH to work for CSO 2s, it might also work for other, larger, jets. This could bring about a fundamental shift in our understanding of the launching of relativistic jets in AGN.

Key Astrophysical Questions Arising from Recent CSO 2 Studies:

1. Is the cutoff in CSO 2 sizes shown in Fig. 7.7 real or are we being misled by small numbers?
2. If the cutoff is real, then what causes this?
3. Are the vast majority of CSO 2s caused by the capture of a single star by an SMBH in a galactic nucleus, as hypothesized by Readhead et al. 2023?
4. If not, then does their energy derive from the spin of the SMBH, as hypothesized by Readhead et al. 2023, or from the accretion disk, in manner similar to that operating in dwarf novae, and if not one of these mechanisms where does their energy derive from?
5. Is the distribution of CSO 2s in the (P, D) plane telling us that the jet power is constant or increasing with size in CSO 2s?
6. Will the smallest CSO 2s resolvable at higher frequencies, or with a Near Earth Orbiting satellite, provide a useful test-bed for the early life of FR II, when we know that the jet power must be increasing?

These are all interesting questions that have the potential of opening a completely new window on jetted-AGN, and very likely causing paradigm shifts in our understanding of AGN, by uniting time domain studies (and possibly jetted tidal disruption events) with structural VLBI studies. Our hypotheses and questions are far from proven or answered, but they are intriguing enough to make arguments for further study compelling.

These hypotheses and questions can be addressed comprehensively only by increasing the number of CSOs in complete samples by several orders of magnitude. We must increase the numbers of CSOs to the 1000s and push down in the luminosity function by three orders of magnitude so that low luminosity CSOs can be observed

at high redshifts. We anticipate very rapid growth in studies of CSOs with the DSA-2000 playing a critical role in what will have become a major new area of study of AGN, relativistic jets, tidal disruption events, and stellar populations in the environs of SMBHs in the nuclei of elliptical galaxies.

DSA-2000's impact

Existing facilities can, at most, increase the sample of CSOs under study to about 100 bona fide CSOs in complete samples. This will be sufficient to confirm indisputably, the sharp cutoff observed in CSO 2s by Kiehlmann et al. 2023a in just the 17 objects shown in Fig. 7.7. However, it is essential to extend the numbers of CSO 2s to the 1000s and to push down in the luminosity function by three orders of magnitude to where low luminosity CSO 2s can be observed at high redshifts. The DSA-2000 is the ideal CSO 2 search engine in view of its frequency coverage and sensitivity and cadence. CSO 2s show fractional variability of less than 20%/yr, and the cadence of once every 4 months is ideal for discriminating between CSOs and blazars. The DSA-2000 will identify many thousands of compact, slowly varying radio sources which will be CSO candidates that can then be followed up with ground-based VLBI that includes at least one large antenna, such as the GBT, which is needed to reach the required sensitivity levels. We are, in parallel, developing the case for a Near Earth Orbiting (NEO) satellite to extend the resolution by a factor ~ 2.5 and provide exceptional dynamic range, that would enable CSO 2s of size ~ 1 pc to be imaged and the structural variations to be monitored. The DSA-2000 is therefore essential for opening this important new window on SMBHs and the launching of relativistic jets.

System requirements / desired additions to baseline design

N/A

7.7 Census of relativistic jets at the highest redshifts

Authors: Eduardo Bañados (MPIA), Fabian Walter (MPIA)

Summary

Relativistic radio jets are thought to be important for black hole growth and co-evolution with host galaxies. The DSA-2000 will provide a complete census of radio jets to the epoch of reionization at $z \gtrsim 6$, reaching more than one order of magnitude deeper than even the deepest existing L-band observation of a source at this cosmic epoch. The DSA-2000 will also reveal young jets turning on/off and play a key role in unveiling the obscured accreting supermassive black holes in the early Universe.

State of the Field

Quasars—powered by $\gtrsim 10^9 M_\odot$ accreting supermassive black holes (SMBHs)—are among the most luminous objects known in the Universe. They can be found and studied in detail to the highest redshifts. The last decade has seen a surge in the population of SMBHs within the first Gyr of the Universe, the so-called epoch of reionization. Now more than 500 quasars are known at $z > 5.3$ (Fan, Bañados, and Simcoe 2023). The current redshift records are at $z \sim 7.5$ (Bañados et al. 2018; Wang et al. 2021), but the most distant of such quasars with known powerful relativistic radio jets is at $z = 6.8$ (Bañados et al. 2021).

Most current efforts focus on identifying type-I or unobscured quasars. However, radio emission prevails even in cases of extreme obscuration ($N_H > 1.5 \times 10^{24} \text{ cm}^{-2}$). It can therefore be used to aid the selection of obscured quasars, which might be one of the prevalent modes of SMBH growth. Recently, Endsley et al. 2022 identified the first obscured quasar at $z \sim 7$, thanks to strong radio emission (Fig. 7.10). Notably, this obscured quasar was found in the 1.5 deg^2 COSMOS field, while similar but unobscured quasars are much rarer ($\sim 0.001 \text{ deg}^2$; Endsley et al. 2023).

Powerful radio jets are thought to play a key role in SMBH growth and SMBH/galaxy co-evolution (Volonteri, Silk, and Dubus 2015; Hardcastle and Croston 2020). Moreover, the identification of radio sources at the highest redshifts will enable unprecedented studies of the epoch of reionization by detecting 21 cm absorption due to the intervening neutral intergalactic medium (Thyagarajan 2020). The identification of a larger number of jetted sources has been mainly limited by the sensitivity of all-sky radio surveys (Fig. 7.10).

DSA-2000's impact

DSA-2000 will provide a complete census of relativistic jets within the first Gyr of the Universe. Indeed, DSA-2000's unprecedented all-sky sensitivity will detect sources with $L_{1.4 \text{ GHz}} \gtrsim 10^{23.2} \text{ W Hz}^{-1}$ at $z \sim 7$. At those luminosities, we will detect not only relativistic jets but also sources like the local high-excitation radio galaxies, whose radio emission is from a combination of AGN and star formation, a regime thus far unexplored at high redshift (Ceraj et al. 2018).

Time domain quasar studies at high redshift are in their infancy. Recent multi-epoch radio surveys like VLASS have revealed significant radio variability on a couple of $z > 6$ radio-bright quasars, measurable in just a few years (Bañados et al. 2023). The proposed cadence for DSA-2000 will not only enable an additional method to select the highest redshift AGN but it can also identify young jets turning on/off and constrain SMBH growth models (Nyland et al. 2020).

DSA-2000, in combination with the new generation of optical/NIR all-sky surveys (e.g., Rubin/LSST, Euclid, Roman), will enable the discovery of obscured AGN, which are thought to be an important phase

for SMBH growth. These obscured AGN are expected to outnumber the type-I quasar population, but thus far, only one is known in the epoch of reionization (Endsley et al. 2022, see Fig. 7.10).

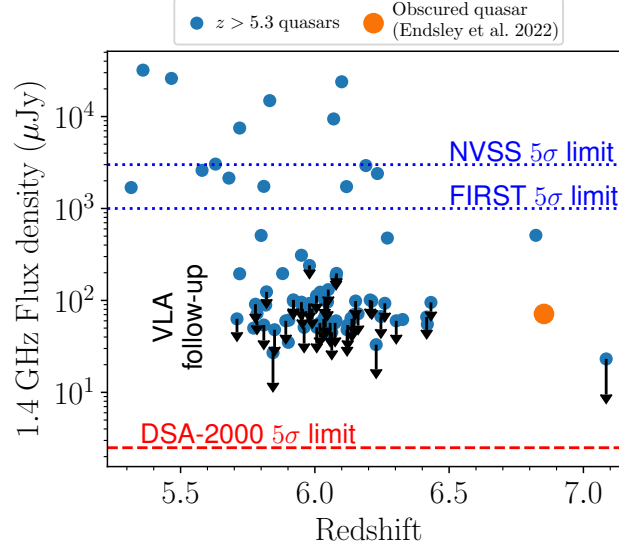


Figure 7.10: All L-band (~ 1.4 GHz) detection/limits of $z > 5.3$ quasars from large radio surveys or VLA follow-up observations. The orange circle marks the only obscured quasar known in the Epoch of Reionization (Endsley et al. 2022). The DSA-2000 will reach more than 1 order of magnitude deeper than even the deepest existing L-band observation of a high- z quasar (Momjian et al. 2014) — DSA-2000 will enable a full census of relativistic jets at the highest redshifts.

System requirements / desired additions to baseline design (see table below)

The baseline design is already an excellent match to the high- z quasars science case. If possible, pushing to lower declinations would have a critical positive impact on the census of the earliest jets, even if the sensitivity is slightly worse than the rest of the survey.

Table 7.2: Project requirements compared to DSA-2000 baseline reference design

	DSA-2000 baseline reference design	match to project
Declinations	$\delta > -31^\circ$	OK, but the lower, the better
Spatial resolution	3.5"	✓ 18 kpc at $z = 7$. Unresolved.

7.8 Weak Lensing Cosmology with the DSA-2000

Authors: Liam Connor

Summary

Weak gravitational lensing is a powerful probe of the Universe’s composition and expansion history, and is an essential tool for constraining the physical nature of dark energy. Weak lensing imparts a distortion on distant galaxy shapes known as “shear”, causing a separation-dependent correlation between galaxy shapes that is determined by the Universe’s large scale structure and its evolution with time. Measuring the power spectrum of this cosmic shear allows us to constrain the cosmological parameters. The large number of radio galaxies detected by DSA-2000 could enable the first significant radio weak lensing experiment. This would require a serious effort in shear calibration and super-resolution, but may end up being a powerful independent probe of cosmology. See our paper for more details^a.

^a<https://arxiv.org/pdf/2111.03249.pdf>

State of the Field

Nearly all significant advances in weak lensing cosmology have come from Optical/IR and CMB data. In the radio, few surveys thus far have had sufficient angular resolution, sensitivity, and sky coverage to detect the large numbers of SFGs required to do weak lensing cosmology. However, there may be an opportunity with the DSA-2000 to carry out a valuable weak lensing survey thanks to its enormous number of galaxies and their deep redshift distribution. Based solely on the areal density of sources and their redshift distribution, DSA-2000 has significantly more constraining power than DES or SKA1-mid, and is comparable with Euclid. If it worked, having a radio weak lensing measurement would be a valuable complement to upcoming OIR experiments, because the lensing signal is chromatic while systematics are not. **It must be said, however, that weak lensing is very difficult and is typically systematics limited.** Many person-years have been spent preparing for weak lensing analysis on Euclid, LSST/Rubin, and Roman, not to mention the work that has already been done on the Dark Energy Survey (DES) or in the CMB. For this reason, a weak lensing experiment on DSA-2000 would require a concerted effort and imported expertise from the OIR; a single radio astronomy postdoc almost certainly could not do this alone.

DSA-2000’s impact

Here I offer the strengths and weaknesses of the DSA-2000’s WL prospects.

Pros:

- Large number of sources, good areal density, and deep redshift distribution
- PSF can be forward modeled, known a priori (unlike OIR)
- Polarization information for intrinsic alignment
- Provides a complementary measurement to OIR WL experiments, where systematics are different

The last bullet may be the most significant. WL is a primary science driver for space-based NIR experiments such as Euclid and Roman, not to mention surveys such as LSST. For this reason, a measurement of the same signal but at radio wavelengths could be valuable. We could cross-correlate the two surveys, allowing for the mitigation of systematics.

Cons:

- *Relatively poor resolution (3.5'') compared with small median SFRG size (0.5'')*
- *Calibration / analysis infrastructure does not exist for WL at long wavelengths*
- *Requires super-resolution—implications of such algorithms on shear calibration is not clear*
- *Need redshifts. SPHEREx galaxies catalog could be used, but needs to be folded into an analysis pipeline*

System requirements / desired additions to baseline design

POLISH requires image plane data and a well-understood PSF. As long as both are available, a model can be trained for deconvolution and super-resolution.

7.9 Strong gravitational lensing on DSA-2000

Authors: Liam Connor

Summary

Strong gravitational lensing of distant galaxies enables a variety of applications in cosmology and astrophysics. The dark matter distribution in lensing halos can be constrained, time-delay cosmography of special systems provides a measurement of H_0 , high redshift sources can be discovered that would not have been detectable in the absence of lensing magnification, etc. Strong lensing is a rare phenomenon, meaning a large sample of extragalactic sources is required to amass a sizeable collection of lensed systems. Lensing is also highly redshift dependent, with an optical depth increasing as $\sim z^3$ for sources within ≈ 1.5 . DSA-2000 is therefore an excellent survey instrument for a strong lensing sample: It will find 1 billion radio sources with a significantly deeper redshift distribution than strong lensing surveys in the OIR such as LSST/Rubin and Euclid. One limitation is the DSA-2000's moderate spatial resolution, which will limit the number of systems whose Einstein radius is below our PSF scale. We argue that this can be mitigated with super-resolution, allowing for the discovery of $\sim 10^5$ strong lenses in the CASS.

State of the Field

To date, there are only $\mathcal{O}(10^3)$ known strong lensing systems. Fewer than 10% are detected in the radio. However, upcoming OIR surveys will find tens of thousands of lenses led by the Rubin Observatory and Euclid. One significant hurdle will be identifying strongly lensed galaxies in the enormous datasets that coming wide-field experiments will produce. Indeed, a sub-discipline of strong lensing has emerged whose goal is to develop the best lens-finding algorithms. Metcalf et al. (2018)¹ compared 24 lens finding algorithms on a mock survey. The models that performed the best were typically learning based. On DSA-2000 we will have to build a custom lens finding model that knows about our PSF and the morphologies of radio continuum sources. This will likely be a convolutional neural network. We will have to fold in multiwavelength information to confirm lens candidates, for example identifying a lens galaxy in NIR with SPHEREx.

DSA-2000's impact

The DSA-2000 could increase the sample of radio strong lenses by a factor of ~ 1000 . My impression, as an outsider, is that the name of the game is to find as many systems as possible such that one can identify special systems for each application. For example, time-delay cosmography requires multiply imaged time-variable quasars behind lensing galaxies whose mass distribution can be easily modelled. In Wong et al. (2019)^a the authors use just six lensing systems as a gold sample. “Jackpot systems” have two Einstein rings—rare events that require a much larger sample to identify. Many of these lensing systems will be co-detected by Roman, Rubin, or Euclid. This multiwavelength information will be valuable for studying special systems and for confirming each survey's candidates. In addition, radio polarimetry allows one to measure the magnetic field strengths of lensing halos thanks to differential Faraday Rotation.

^a<https://arxiv.org/abs/1907.04869>

¹<https://arxiv.org/abs/1802.03609>

System requirements / desired additions to baseline design

As long as the antenna configuration remains roughly the same, most choices that will impact strong lensing can be made in software. POLISH requires image plane data and a well-understood PSF. As long as both are available, a model can be trained for deconvolution and super-resolution.

7.10 Deep radio surveys as a powerful complement to next generation (sub)mm wave surveys.

Authors: Scott Chapman, Ryley Hill, South Pole Telescope collaboration

Summary

The SPT-SZ survey unexpectedly identified 85 bright, dusty point sources ($S_{1.4\text{mm}} > 20\text{mJy}$), 90% of which ALMA showed were strongly lensed submm galaxies (SMGs). However, 10% have been characterized as unlensed, dense cores of $z=3-7$ protoclusters of galaxies with integrated SFRs $> 10,000 M_{\odot}/\text{yr}$. Radio-AGN in massive clusters are important for feedback in the intra-cluster medium (ICM) and central brightest cluster galaxy. The radio loud AGN detected by ATCA in the SPT2349 protocluster is of pivotal importance for understanding and interpreting the early forming structure. Deep MeerKAT followup has characterized the radio spectral index and detected star forming cluster members. Radio observations have the unique possibility to efficiently followup and identify these mm-wave sources in large surveys. In addition to providing positions, the strength of the radio emission itself can separate AGN from star forming sources. DSA-2000 can play an important synergistic role with upcoming (sub)mm-wave surveys like CCAT-prime and CMB-S4.

State of the Field

The South Pole Telescope (SPT) survey (Carlstrom et al. 2011) covering 2500 deg^2 was initially aimed at a Sunyaev-Zeldovich (SZ) cluster survey along with primary CMB science. The second generation receiver, SPT-Pol, brought polarization sensitivity over 1000 deg^2 and the first maps of the B-mode CMB polarization allowing characterization of the lensing B-mode spectrum. Currently SPT is in its third generation survey, “3G”, covering 1000 deg^2 to unprecedented depths at 1.4mm, 2mm, and 3mm.

The SPT-SZ survey unexpectedly identified 85 bright, dusty point sources (Vieira et al. 2010), 90% of which are strongly lensed submm galaxies (SMGs), unveiled by ALMA (Vieira et al. 2013). However, 10% appeared to be unlensed, incredibly luminous sources in the far-IR. ALMA followup has revealed that they break up into numerous submm sources, and has shown them to be candidate cores of $z=3-7$ protoclusters of galaxies (Miller et al. 2018; Chapman et al. 2023). The SPT-3G survey is increasing these numbers by $100\times$, paving the way to find many hundreds of such forming clusters of galaxies, but making followup challenging. Future surveys such as CMB-stage4 will do the same over the majority of the accessible sky from Chile.

Radio observations have the unique possibility to efficiently followup and identify these mm-wave sources. In addition to providing positions, the strength of the radio emission itself can separate AGN from star forming sources. A recent example is in the SPT2349-56 protocluster at $z=4.3$ (Miller et al. 2018; Hill et al. 2020; Rotermund et al. 2021, Chapman et al. 2023). This system is the brightest ‘unlensed’ SPT source found in SPT-SZ. The 1’ ‘point source’ found by SPT has now been resolved by ALMA into 35 far-infrared luminous galaxies at $z\sim 4.3$. Their total L-IR is more than $10^{14} L_{\odot}$, corresponding to a SFR of almost $20,000 M_{\odot}/\text{yr}$. Perhaps its most defining characteristic is that it is the most concentrated protocluster system known, and may represent the progenitor of the most massive present day cluster in the Universe, even more massive than the Coma cluster.

Curiously, no AGN were originally identified in SPT2349 in any (sub)mm or optical indicators, at odds with protoclusters typically having overdensities of AGN/QSOs, or even being identified by them in the first place. ATCA observations at 2 GHz ($25\mu\text{Jy}$ RMS) were recently able to identify a luminous radio-loud AGN in

the core of SPT2349. Deep MeerKAT followup at 816 MHz ($7\mu\text{Jy}$ RMS) were then able to robustly characterize the radio spectral index, and even detect several other cluster members through their star forming radio-FIR correlation. For context, with radio surveys at $> 10^{23}$ W/Hz (e.g., NVSS – Condon 1998), with source densities about $1/100$ arcmin², sources are identified out to redshifts of 5, and all are radio-loud AGN. Between 10^{21} and 10^{23} W/Hz (e.g., JVLA deep surveys with $> 10\mu\text{Jy}$ sources and $4/\text{arcmin}^2$), radio sources are mostly star forming galaxy hosts. However, we caution that only 10% of AGN are radio-loud, and radio on its own is not a complete survey of AGN.

Radio-AGN in massive clusters are important for feedback in the intra-cluster medium (ICM), regulation and growth (evolution) of the cluster core and central brightest cluster galaxy. Thus detecting the radio loud AGN in SPT2349 is of pivotal importance for understanding and interpreting the early forming structure. As in Chapman et al. (2023), we can use the radio power to estimate (lower limit) jet power, and therefore energy injection into the ICM. They concluded that for SPT2349, this is sizeable amount of energy given the potential well of the $10^{13} M_{\odot}$ halo constrained from the velocity dispersion of the cluster. The radio power can even be reasonably used to infer a range of likely Xray luminosities (to within a factor of order 10), and from that derive the accretion rates onto the super massive black hole, setting the stage for targeted X-ray followup.

DSA-2000's impact

For the SPT-3G survey, these studies suggest that we should get the best/deepest radio data we can on protocluster sources and study the radio-loud AGN, as well as the other cluster members. Indeed we should study all SPT sources in the radio. To this end, a large MeerKAT program is underway (PIs: Roger Deane, Joaquin Vieira), aiming to match this $7\mu\text{Jy}$ RMS depth at 816 MHz over 100 deg^2 . The capability of DSA-2000 (Hallinan et al. 2019) in surveying large areas (1000's of deg^2) at even greater sensitivities is an obvious synergy with upcoming surveys at (sub)mm wavelengths with CCAT-prime, Simons Observatory, and CMB-S4, and in the longer term with 30-50m submm wave single dish telescope concepts such as ATLAST. Radio observations have the unique possibility to efficiently followup and identify these mm-wave sources. In addition to providing positions, the strength of the radio emission itself can separate AGN from star forming sources. The DSA-2000 sensitivity will identify and classify many 100,000's of mm-wave sources out to redshifts of even 10.

System requirements / desired additions to baseline design

N/A

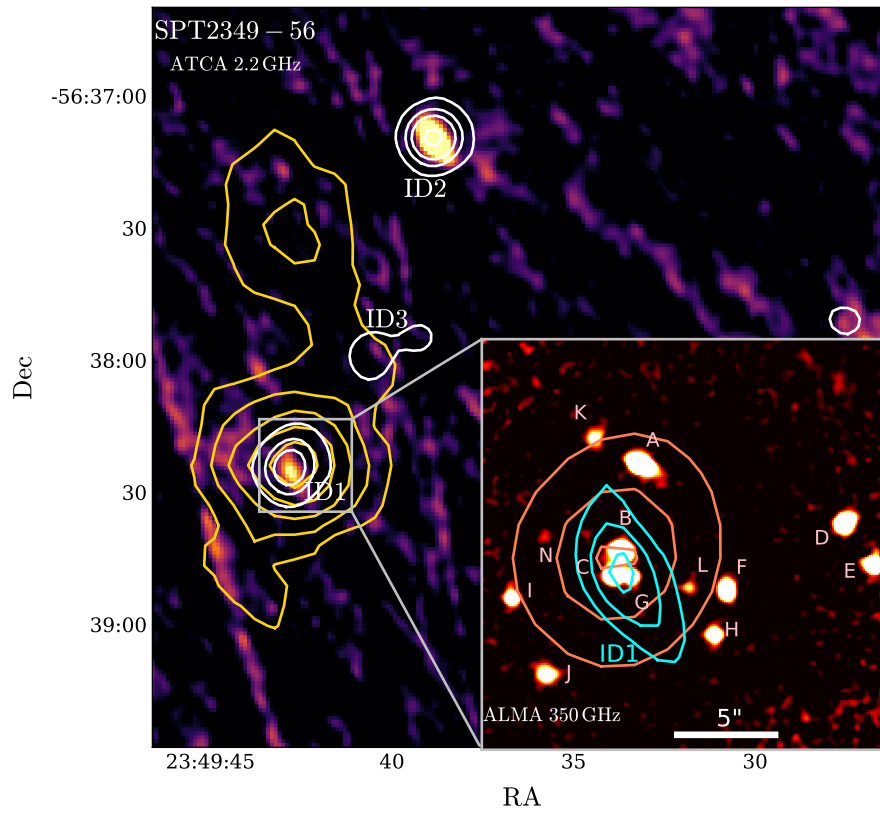


Figure 7.11: The $z=4.3$ SPT2349 field observed by ATCA at 2GHz (background image). MeerKAT 816MHz detected sources are shown as white contours. The SPT2349 850 μ m emission (from LABOCA with 19'' beam) is shown as gold contours. (*INSET*) ALMA resolves the 850 μ m emission into 30 individual galaxies in C+, the brightest of which are evident in this continuum image. ATCA and MeerKAT contours identify the central BCG galaxy as the radio-loud AGN.

7.11 AGN polarimetry

Authors: Mark Lacy (NRAO)

Summary

The DSA-2000 will measure the polarization properties of ~ 3 million active galactic nuclei (AGN). This will enable vastly improved studies of foreground Faraday screens due to the Milky Way and nearby galaxy clusters, as well as statistical studies of depolarization of AGN by their surrounding haloes.

State of the Field

Faraday rotation – the rotation of the plane of polarization by a magnetized plasma proportional to the integral of the line-of-sight magnetic field times the electron density – is an important diagnostic of cosmic magnetic fields. AGN can provide valuable insights into the properties of magnetized plasma in two ways. First, the plane of polarization of background AGN can be Faraday rotated by foreground screens such as the Milky Way, or the intracluster medium of an intervening cluster of galaxies. Second, magnetized plasma in the immediate environment of the radio source (perhaps mixed with synchrotron-emitting plasma) can lead to large amounts of Faraday rotation and consequent depolarization.

7.11.1 AGN as background sources

By using the Faraday rotation of polarized light from background AGN we can map the magnetic field of the Milky Way. The resolution of this map is constrained by the density of AGN on the sky whose Faraday rotation can be accurately measured. Using the NVSS survey, with a polarized source density $\approx 1 \text{ deg}^{-2}$ (Taylor et al. 2009) naturally limits the resolution to degree scales, though some areas of the sky now have better coverage e.g. from LoFAR (Hutschenreuter et al. 2022). Future surveys such as POSSUM (Anderson et al. 2021) will deliver even denser backgrounds, $\approx 20 - 30 \text{ deg}^{-2}$, and also allow the Faraday screens due to foreground galaxy clusters to be mapped (Figure 1).

7.11.2 Polarization as a diagnostic of AGN environments

Synchrotron radiation is emitted with an intrinsic polarization of $\approx 70\%$, but a typical radio AGN has a measured polarization of only $\approx 5\%$ (Beck & Gaensler 2004; Hales et al. 2014). Some of this depolarization is due to line-of-sight and beam averaging, but much also arises in the immediate environment of the source itself. Detailed studies of polarized radio sources (e.g. Baidoo et al. 2023) show that the depolarizing medium has structure on kpc scales. While it is often unclear whether the depolarization occurs in the immediate vicinity of radio lobes, or further out in the halo of the host galaxy and any surrounding cluster, statistical studies, e.g. of the Laing-Garrington effect (an anti-correlation of jet-sidedness with depolarization; Laing 1988; Garrington et al. 1988) and studies of the depolarization of sources as a function of redshift (e.g. Goodlet & Kaiser 2005) suggest that at least some of the depolarization is from the halo. However, only a few tens of sources have been studied to date, making definitive conclusions difficult to draw.

DSA-2000's impact

The dense background of polarized sources expected from DSA-2000 ($\sim 100 \text{ deg}^{-2}$) will greatly increase the possible range of Faraday screen studies. In particular, detailed studies of the magnetized ICM of nearby galaxy clusters could be carried out. The higher angular resolution than prior studies at ≈ 1

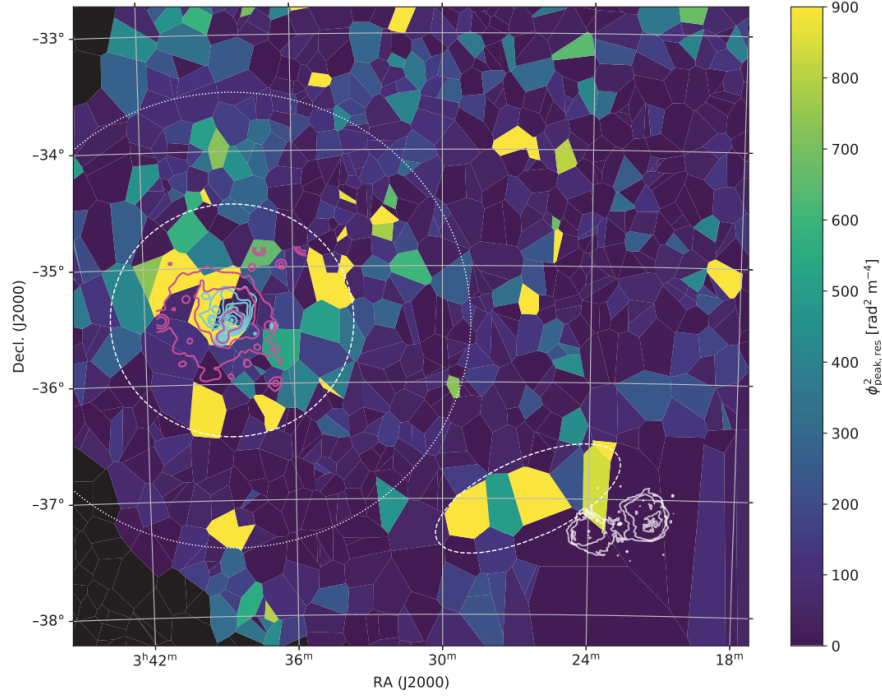


Figure 7.12: A rotation measure map of the Fornax galaxy cluster from the POSSUM pilot survey (Anderson et al. 2020). The main Fornax cluster is to the left (X-ray contours in pink), on the bottom right is the Fornax A radio galaxy (white contours). Note the region of high rotation measure between the cluster and the radio galaxy, possibly indicative of a region of shocked gas from a subcluster merger. The background polarized source density of this study, $\approx 25\text{deg}^{-2}$, is about four times lower than could be achieved with DSA-2000. DSA-2000 will thus allow even higher resolution Faraday rotation maps of nearby clusters and enable mapping of more distant examples at a similar physical resolution.

GHz will result in less depolarization within a beam, increasing the signal-to-noise for polarized light. Combining DSA-2000 polarimetry with VLASS (Lacy et al. 2020) will result in thousands of sources with well-measured depolarization from 0.7-4 GHz at ≈ 3.5 arcsec resolution, allowing large-scale statistical studies of the evolution of magnetic fields and turbulence in the galaxy/cluster haloes surrounding AGN.