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Optical, Radio Continuum and HI Deep Spectroscopic Survey (ORCHIDSS)

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Galaxy evolution is regulated by the continuous cycle of gas accretion, consumption and feedback. Crucial in this cycle is the availability of neutral atomic (HI) and molecular hydrogen. Our current inventory of HI, however, is very limited beyond the local Universe ($z > 0.25$), resulting in an incomplete picture. ORCHIDSS is designed to address this critical challenge, using the powerful combination of 4MOST spectroscopy and sensitive radio observations from the MeerKAT deep extragalactic surveys to trace the evolution of neutral gas and its lifecycle within galaxies across the bulk of cosmic history.

Scientific context

On galactic scales, star formation is regulated by the complex cycling of gas in and out of the interstellar medium (ISM; Kereš et al., 2005). This cycle starts with primordial gas accretion, which fuels star formation and accretion onto black holes. Feedback in the form of stellar winds, supernovae and active galactic nuclei (AGN) jets shock heats the gas and drives outflows. The last stage of the cycle is the cooling of the recycled gas from the hot halo, some of which then accretes into the ISM and restarts the cycle. Large investments have been made in studying the coolest, dense molecular gas and the hottest, most rarefied gas halos of galaxies (with, for example, ALMA, XMM and Chandra). However, the cycling of cold atomic gas, the cleanest probe of the ISM, is poorly understood. This gas can be traced by the 21-cm transition line of neutral hydrogen (HI), but sensitivity limits have restricted such studies to the local Universe (Catinella & Cortese, 2015).

In the local Universe, the instantaneous star formation rate (SFR) in galaxies is much more tightly connected to molecular gas than to the neutral atomic gas from which molecular clouds condense (for example, Bigiel et al., 2011). Galaxy evolution models that incorporate this connection have been able to account for the sharp increases with redshift of the cosmic SFR density and the cosmic molecular gas mass fraction (for example, Davé et al., 2020). However, these models’ predictions of more modest redshift evolution in the cosmic HI density can presently be compared only to absorption-line studies, where the exact relationships between galaxies and absorbers remain uncertain, and where possible relationships between HI content and star formation averaged over Gyr timescales cannot be explored at all. Testing these models and fully understanding the buildup of stellar mass over cosmic time requires directly observing all components of the gas reservoirs in galaxies, out to significant cosmological redshifts that have not been accessible until now.

Thanks to the ongoing revolution in radio astronomy, it is now possible to probe these regimes and begin to tackle a number of key challenges in our understanding of galaxy formation: what is the cosmic history of neutral hydrogen? what is the lifecycle of gas within galaxies? and how does feedback impact the gas reservoirs of galaxies?

At the forefront of this revolution is the MeerKAT telescope, its radio continuum surveys now simultaneously providing one of the most reliable, obscuration-free, probes of star formation and a means of tracing black hole accretion in AGN. Furthermore, its surveys of the 21-cm HI emission line provide a powerful new probe of the ISM of galaxies up to $z = 1.4$.

MeerKAT’s flagship deep extragalactic surveys, MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE; Heywood et al., 2022) and Looking at the Distant Universe with the MeerKAT Array (LADUMA; Blyth et al., 2016), are breaking new ground in the study of neutral atomic gas in galaxies. MIGHTEE will directly detect HI in several hundred galaxies at $z < 0.2$, and a few of the rarest, most HI-massive galaxies out to $z = 0.5$ thanks to the large volume probed over its multiple fields (> 10^7 Mpc^3 at $0.45 < z < 0.55$). Reaching ~ 4.5 times deeper in HI sensitivity at $z < 0.5$ and extending frequency coverage of HI to $z = 1.4$ in a single field, LADUMA will detect larger samples of lower-mass galaxies and enable detection of the most HI-massive galaxies out to $z = 1$. Despite

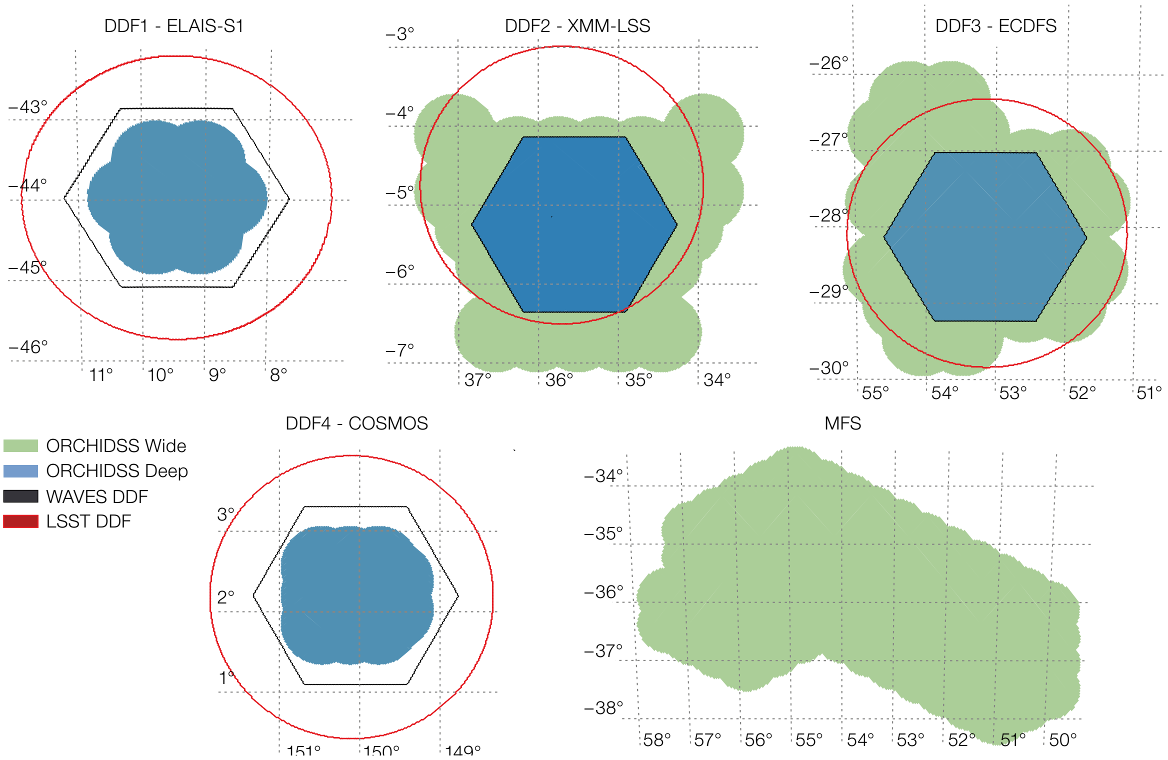

Figure 1. Planned survey fields and maximum potential footprint for the ORCHIDSS Survey. The ORCHIDSS Deep fields (blue shading) align with the WAVES Deep Drilling Fields, targeting MIGHTEE radio-detected sources out to $z_{\mathrm{phot}} < 1.4$. ORCHIDSS Wide targets will be drawn from the MIGHTEE and MFS coverage to probe a wider range of cosmic environments out to $z_{\mathrm{phot}} < 0.57$.

these substantial advances, however, the 21 cm flux-limited nature of these surveys means that, by themselves, they will preferentially detect only the most HI-rich galaxies.

The full potential of MeerKAT's surveys will only be realised if they are matched with extensive optical spectroscopy. By building a large, representative sample of galaxies with accurate spectroscopic redshifts, we can spectrally align and stack the radio data to extract HI measurements below the MIGHTEE and LADUMA noise thresholds (Chowdhury, Kanekar & Chengalur, 2022; Pan et al., 2022), revealing the neutral gas properties of representative samples of the full galaxy population over much of cosmic history.

Specific scientific goals

Combining the deep radio observations offered by MeerKAT and the high-multiplex optical spectroscopy offered by 4MOST, the Optical, Radio Continuum and HI Deep Spectroscopic Survey (ORCHIDSS) will address the key scientific challenges outlined below.

The cosmic history of neutral hydrogen

Galaxy evolution is driven by the availability of atomic and molecular hydrogen in the ISM of galaxies. The large, homogeneously selected and highly complete spectroscopic samples provided by ORCHIDSS will allow us to trace the HI content in normal galaxies out to $z = 1.4$. ORCHIDSS will provide the most reliable measurement of the evolution of the cosmic HI density and HI mass function out to the epoch where galaxy formation peaked.

The lifecycle of gas in galaxies

The stellar growth of galaxies is regulated by the continuous cycle of gas accretion, consumption and feedback. The parameters governing the flow of this gas cycle, such as the primordial gas accretion rate and efficiency of stellar feedback, are highly uncertain and yet vital to obtain for any successful model of galaxy evolution (Somerville & Davé, 2015). For the first time, ORCHIDSS will measure these parameters via the fundamental relations between the neutral gas content of galaxies and key physical properties (SFR/stellar mass/metallicity; Davé et al., 2020), measured by 4MOST and the wealth of available photometric data, over 9 Gyr of cosmic history.

The role of feedback in regulating the gas reservoir of galaxies

MeerKAT will identify star formation and AGN activity across the bulk of cosmic history with a single, unified dataset, unbiased by obscuration. ORCHIDSS will enable us to relate that accretion and SFR to gas properties. With kinematic constraints on both the ionised gas (via optical emission/absorption lines) and neutral gas components providing direct evidence of outflows, we will explore the complex interplay between star formation/AGN fuelling, activity and feedback for the multi-phase warm gas in galaxies.

Legacy value

ORCHIDSS will enable a huge range of additional science. For example, the combination of large optical spectroscopic samples and MeerKAT's spectral sensitivity will also enable unique measurements of the baryonic Tully-Fisher relation (McGaugh et al., 2000). Moreover, we will probe extreme star formation and galaxy mergers using OH megamasers (Glowacki et al., 2022), with the ORCHIDSS spectra providing both robust disambiguation of HI and OH spectral detections and enabling OH stacking measurements. More broadly, our survey has also been planned with significant legacy value in mind, including but not limited to:

- A complete census of AGN and star formation activity in the Legacy Survey of Space and Time Deep Drilling Fields (DDF). The large and complete samples of AGN observed over the four DDF will allow us to study whether and how key properties of the AGN correlate with host properties like stellar mass and star formation history, as well as with environment and redshift. By enabling robust source classification down to the faintest limits of the radio continuum luminosity function, ORCHIDSS and MeerKAT combined will provide a highly complete, obscuration-free picture of the cosmic accretion and star formation histories since the epoch of peak galaxy formation.
- A platform for the Square Kilometre Array Observatory (SKAO). The spectroscopic samples provided by ORCHIDSS are designed to facilitate HI science beyond the nominal detection limits of MeerKAT. However, as the full 4MOST surveys are completing, the SKAO will be coming into the first stages of operation. The results obtained by ORCHIDSS and MeerKAT will be essential in defining the scope for future SKA HI surveys. Furthermore, as the fields with the best ancillary multiwavelength data in the southern hemisphere, the ORCHIDSS fields will be the natural targets for future SKA deep continuum and HI surveys. Pre-existing spectroscopy will therefore offer huge legacy value for many years to come, as we move from the broad statistical constraints possible with MeerKAT and ORCHIDSS to the resolved 21 cm and radio continuum studies of individual galaxies with the SKA.

Target selection and survey area

Given the strong correlation between SFR and gas mass (Catinella et al., 2018), and that radio continuum provides an obscuration-free tracer of the ongoing SFR, radio continuum surveys offer an extremely efficient means of selecting an HI-rich population. ORCHIDSS will obtain spectra of a highly complete sample of galaxies selected on the basis of their MeerKAT radio continuum fluxes, with additional photometric redshift cuts limiting the sample to redshifts where the 21 cm emission line falls within the available frequency coverage.

The extent and locations of the ORCHIDSS survey fields (illustrated in Figure 1) are defined by the footprint of the deep MeerKAT extragalactic surveys, including MIGHTEE (which overlaps and extend beyond the four DDF) and the very deep LADUMA field (CDFS) outlined above, supplemented with the MeerKAT Fornax Survey (MFS). The survey is split into two tiers:

- ORCHIDSS Deep will extend the spectroscopic coverage of the four WAVES Deep Drilling fields to higher redshifts and fainter optical magnitudes, targeting ~ 120 000 radio continuum detections down to the flux limit of the MIGHTEE survey ($S_{1.3\ \mathrm{GHz}} \geq 15\ \mu\mathrm{Jy}$) that have photometric redshifts $z_{\mathrm{phot}} < 1.4$.
- ORCHIDSS Wide will target a further ~ 75 000 radio-detected sources at $z_{\mathrm{phot}} < 0.57$ within the remaining area of the full MIGHTEE and MFS footprints (green shaded areas in Figure 1), doubling the cosmological volume in which sensitive HI constraints can be made at $z < 0.57$ and enabling critical measurements of the dependence of HI content across the full range of cosmic environments.

Across both tiers, our sample will be complete down to the typical SFR of Milky Way-like galaxies across their respective redshift ranges and complete for all powerful AGN, regardless of obscuration. Our sample selection and scientific goals are carefully chosen to complement existing and planned spectroscopic surveys and to maximise the synergy with current and future radio facilities in the southern hemisphere.

Spectral success criteria and survey figure of merit

The primary requirement for individual ORCHIDSS spectra is the measurement of a high-confidence spectroscopic redshift. Given that, our spectral success criteria will match those of the WAVES 4MOST Consortium survey (Driver et al., 2019), with a requirement that a redshift be measured by the 4MOST Extragalactic Analysis pipeline with > 90% confidence. We note that while our planned sample selection does not include an explicit optical magnitude cut, the selection based on activity ensures that redshift confirmation remains efficient, with over 90% of targets meeting the success criteria within the maximum exposure times of three and seven hours (Wide and Deep respectively).

Finally, since ORCHIDSS science is driven by maximising the spectroscopic completeness within a limited target sample, our figure of merit (FoM) is defined such that FoM = 0.5 at 90% completeness.

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