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From star-formation to recombination: expanding our view of the radio recombination line universe

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Summary

Galaxies are large gravitationally-bound collections of stars (all the planets that surround them), gas, dust, cosmic rays, black holes, and dark matter. Large clouds of gas and dust, referred to as the interstellar medium, fill most of a galaxy's volume. Intermixed are shining points of stellar light — stars with a whole slew of different sizes, masses and brightnesses. High energy particles moving at relativistic[8] speeds, known as cosmic rays, zip around galaxies due to influences by magnetic fields. The center of most galaxies contains a super massive black hole. In addition to matter which interacts with light in the electromagnetic spectrum, there is also "dark matter" which influences galaxies gravitationally.

Understanding how these basic components coalesce, evolve, and influence a galaxy guides modern astrophysical research. When we look in regions of galaxies where stars are forming, it resembles a bubbling cauldron — for example, see the Cygnus X star-forming in Figure 5.23. As new stars form in (cold) interstellar clouds, they create pockets of ionized[9] and blown out gas. These bubbles expand and often spill out from a galaxy's disk. Large interstellar clouds exist in different characteristic phases (with various temperatures, densities and sizes) — largely reflecting the global galaxy-wide influence of stars. Yet the properties of clouds set the conditions for new star formation. If the supermassive black hole has an accretion disk that is actively emitting copious radiation or has formed jets of streaming cosmic rays, that may also profoundly influence the make up of a galaxy. A complex, interdependent ecosystem is created by the interplay of these physical processes.

Although intricate, the balance acting between these processes does set up some characteristics features of a galaxy and its life cycle that astronomers have come to gather.

What is the lifecycle of interstellar clouds?

Figure 5.24 summarizes the lifecycle of stars and interstellar clouds in a galaxy that is much like our Milky Way.

Gas that is cold (10 K above absolute zero!) and that largely consists of molecules (rather than single atoms) forms coherent gravitationally-bound clouds. A turbulent event[10] in the galaxy causes instabilities and over-densities in the so-called giant

[8] moving at velocities that are a significant fraction of the speed of light

[9] Ionized gas is made up of atoms that have electron(s) removed.

[10] Turbulence can come from a nearby exploding star or larger structure in the galaxy like a spiral

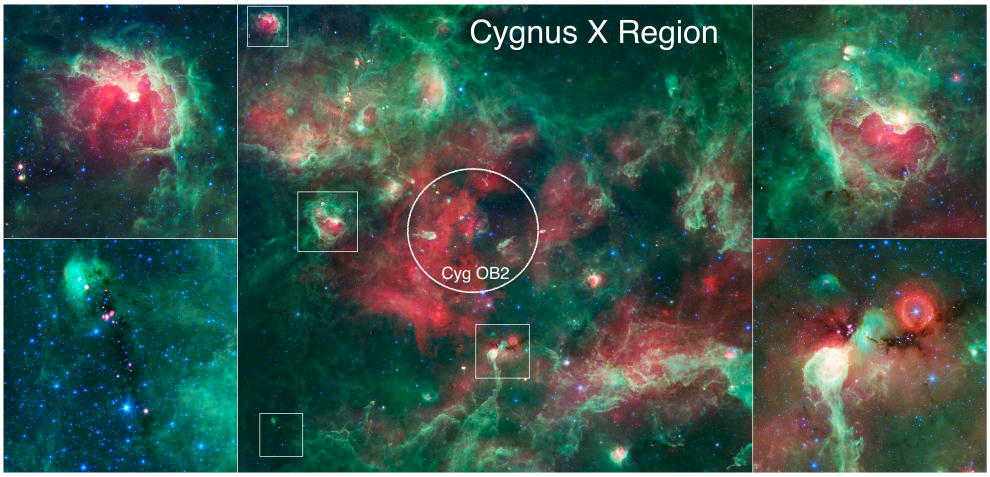


Figure 5.23: The Cygnus X star-forming region, a bubbling cauldron of star birth surrounding the Cyg OB2 association — observed with the *Spitzer* Space Telescope: 3.6 μm in blue, 4.5 μm in blue-green, 8.0 μm in green, and 24 μm in red. Irradiated surfaces of molecular clouds appear bright in green-white. Massive stars that have blown bubbles and cavities in the dust and gas are evident where green-white emission surrounds a bubble of glowing red emission from warm dust (ionized gas). The brightest, yellow-white regions are warm centers of star formation. Tendrils of dust appear green, and stars generally appear as blue point sources. The pillar-like and elongated features directed away from Cyg OB2 have been shaped by the stellar radiation and winds from this massive ($M_\star \approx 2 \times 10^4$ M$_\odot$) association. The boxed zoom-in regions show massive star(s) (formation) in AFGL 2636 (upper left) and DR22 (upper right). The lower left and right (DR15) images show clouds that are so thick to be absorbed at the mid-infrared wavelengths of Spitzer. Young stars, visible as red points, are buried in the dark clouds. Image credit: NASA / JPL-Caltech / Harvard-Smithsonian.

molecular cloud. At this point, the giant molecular cloud collapses as the over dense pockets attract an ever-growing amount of material and new stars form.

Stars fuse elements in their core — for example, four protons (i.e., four hydrogen nuclei) fuse to create a helium nucleus. Stars radiate light and have a gusting wind of cosmic rays at their surface. Stellar radiation, especially from the most massive stars, heats up the surrounding gas and dust, dissociating molecules and stripping atoms of their electrons (ionization). Stellar winds (and even pressure from radiation) effectively push on surrounding clouds, shocking and heating them. Radiation and winds halt collapsing material and destroy the remains of their natal giant molecular cloud, thereby preventing new stars from forming.[11] After a few million years, massive stars are no longer enshrouded in their natal material. At this point in time, their radiation is able to reach large distances, heating the interstellar clouds of the galaxy and maintaining extended and pervasive components of ionized gas.

The life of a star ends when it can no longer fuse atomic nuclei in its core. As stars approach the end of their lives, the outer layers become too heavy to support. Some stars burp out and slough off material from their surface, material made up of the nuclei of "heavy" elements that were fused in their core. The most massive stars end their lives with great explosions called supernovas. With that explosion, heavy elements stream into and enrich nearby gas clouds. The shock wave from the explosion expands outwards, also heating the medium and imparting kinetic energy

arm or due to a collision with another galaxy.

[11] At least, breaking up the cloud and halting star formation happens most of the time. In a smaller fraction of instances, as shock waves (from the winds and radiation) move through the medium, they can cause some regions to collapse in on themselves and in those dense regions new stars actually form. However, the net effect is that more star formation is stopped than gets initiated.

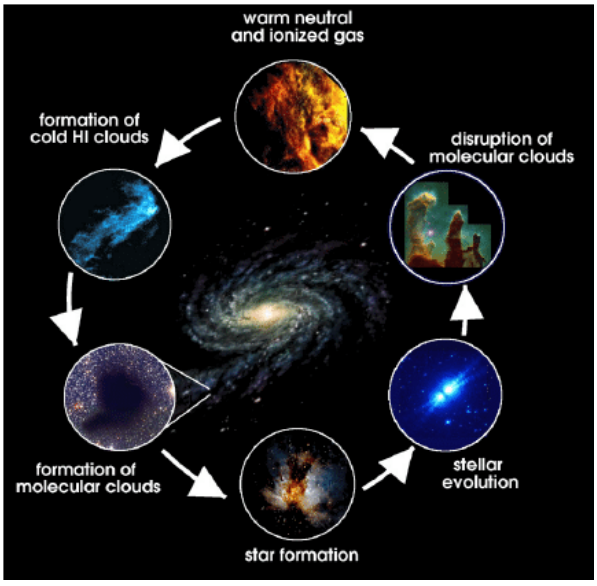


Figure 5.24: The lifecycle of interstellar clouds.

into an outward push.

As stars die off, the interstellar clouds which they have warmed start to cool off too. Sometimes the gas and dust surrounding massive stars or groups of stars has been given such a big push that the clouds are sent speeding away from the galaxy's disk, and far away, they are no longer heated. In any case, the gas clouds cool down. Molecules start to form, the molecules help the cloud to shield itself from radiation, and the material further cools and condenses forming a giant molecular cloud. The conditions for new star formation are set, and the cycle repeats.

How do galaxies evolve?

The origin and evolution of galaxies are closely tied to the cyclic feedback processes between stars and interstellar matter, what astronomers call stellar feedback. Depending on the net amount of heating and cooling that occurs, the interstellar medium equilibrates, forming stratified clouds of characteristic properties. Cloud conditions regulate the number of stars that form. But as we mentioned above, stars also influence the clouds on smaller (non-global) scales by dispersing them, and they may also act as turbulent agents.

Understanding stellar feedback, i.e., the interplay of the different processes involved, is quite challenging because we can not play out the events in real time. They typically occur over thousands to billions of years; so we just get snapshots of the process with our current observations, and we try to piece together different stages of the processes. Creating simulated movies of the entire collective process by incorporating the basic physics that govern it is not fully possible yet (though great progress has been made to understand pieces of it!). Complex interactions transpire on the smallest scales — with chemical networks inside molecular clouds and influential processes occurring from individual stars and solar systems — all the way up to the scale of an entire galaxy.

In the lifecycle I described above, the relationship is mainly framed around the stellar feedback from a single star and a nearby cloud. However, stars are born in groups at similar times and some reside close enough to each other such that their concerted efforts create compounding effects. A typical giant molecular cloud has a mass of about a million times the mass of our sun; if the star formation process is 100% efficient (and if only one type of star is formed), a million of our suns could form from one cloud. Turbulent events that act on clouds usually cause the entire giant molecular cloud to collapse, thus producing a stellar nursery of stars of similar ages and locations in the galaxy.

Even though giant molecular clouds are gravitationally bound, the stars that form within it won't necessarily be bound to one another. However, we do see groups of stars that have formed and are gravitationally bound — we call those star clusters. The most massive and compact star clusters tend to be the most efficient at creating stars. Where in a galaxy these stars form also makes a difference. Within the disk of a spiral galaxy, for example, new stars typically form in spiral arms. Massive and compact star clusters tend to form close to the center of galaxies (as can be seen in Figure 5.25) or promptly when two galaxies merge.

So far, I have described the intimate connection between stars (their locations),

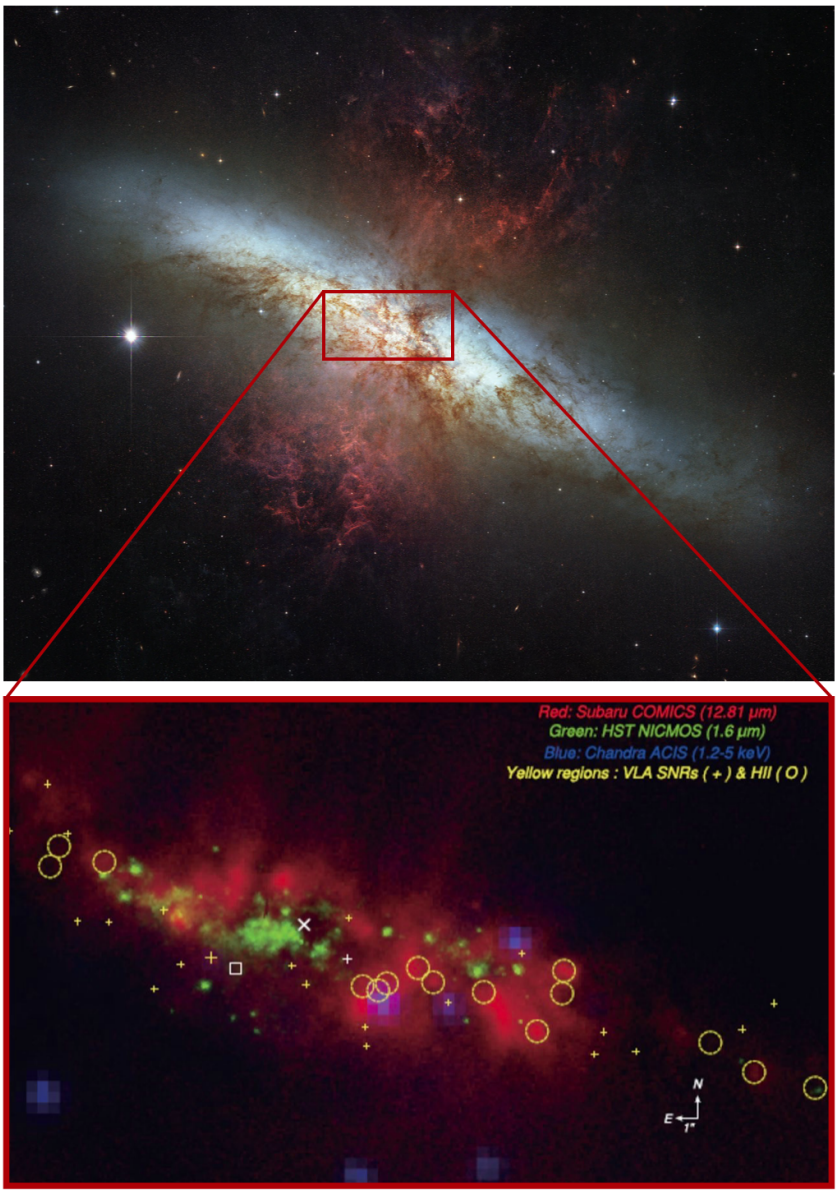


Figure 5.25: In the top panel, the disk of the nearby (3.5 Mpc) edge-on galaxy, M82, glows in white-blue and the prominent galactic winds from the nucleus are traced by the PAH emission in red. Super star clusters (yellow circles) in the nucleus (in the bottom panel) drive the outflow. Image credits: NASA / ESA / The Hubble Heritage Team.

stellar feedback, and the interstellar medium, and this is primarily what I focus on in my thesis. The following are additional factors which are important to the evolution of galaxies but which I do not discuss at length: (i) intergalactic gas that accretes onto galaxies and injects new material into the life-cycle process, (ii) a galaxy's environment and how often it interacts with other galaxies, (iii) an active supermassive blackhole at the center of a galaxy that is gobbling up interstellar matter and whose radiation and/or relativistic jets of hot plasma impact the cycling of intercloud phases, and (iv) the initial over density in space after the big bang which seeded the formation of a galaxy might be a major determinant in a galaxy's properties.

How do astronomers study interstellar clouds and stellar feedback?

To understand the interstellar medium and its interplay with stars using observations, astronomers make detailed, high-resolution studies of individual stars and cloud clumps, use large samples and surveys of astronomical objects to statistically assess physical mechanisms, and make galaxy-wide assessments on how their properties track over cosmic time. In-depth studies are commonly performed within our own Galaxy for example. The proximity allows us to see objects in the Galaxy close up at high resolution, and we have a multitude of ways to detect the gas and infer the influence of physical processes that would not be possible in galaxies that are further away and thus have fainter signals. However, it is often useful to take a bird's-eye-view and observe nearby galaxies in a variety of orientations, which may harbor different environments. Because light travels at a finite velocity ($c = \nu\lambda = 0.7$ billion miles-per-hour)[12], the light that is just reaching us now from the most distant galaxies was emitted when those galaxies were younger. In this way (and since there is evidence that the universe is homogeneous and isotropic), we can observe galaxies as a function of the age of the universe to see how the bulk properties of galaxies evolved over cosmic time.

A beauty of astronomy is that we use the really simple concept of observing light along the electromagnetic spectrum with different wavelengths (frequencies, or energy) to infer the physics and wonders of our Universe.[13] From the simple concept of making 2D pictures at different wavelengths, we infer the presence of astronomical objects, the physical properties of the objects, their 3-dimensional distributions and movements, how objects influence each other, and how they evolve over time (adding a fourth 4th dimension to the 3D picture!).

The main ways we study interstellar clouds through continuum light are: infrared light (wavelengths of $\lambda \sim 0.001 - 0.5$ mm) from dust at a range of temperatures, the emission from free electrons that is radiated at radio wavelengths ($\lambda \sim 5$ mm – 30 m) when the electrons pass close to one another, hot gas emits a continuum of X-ray

[12] In the equation $c = \nu\lambda$, ν is the frequency of light and λ is the wavelength; the speed of light is constant (in a vacuum), so as the wavelength gets smaller the frequency goes up and vice versa, as the wavelength is longer the frequency is shorter and the light has lower energy (since energy is proportional to frequency).

[13] Exceptions to this include directly detecting cosmic rays (high energy particles) from space or new gravitational wave detectors. These observations are so uniquely valuable because they explore the universe in an entirely different way than traditional astronomy.

light, and as high-energy particles collide with interstellar clouds gamma-ray emission — the highest energy photons (with inconceivably small wavelengths, $\lambda < 10^{-11}$ mm) — is emitted.

In addition to continuum emission, another way to observe the constituents of galaxies are through spectral lines. Spectral lines occur when atoms and molecules produce (or absorb) light at specific frequencies. This process takes place whenever the energy of an atom or molecule changes, which takes place relatively often in interstellar clouds. These energy changes might be due to vibrations and rotations of molecules or changes in the configuration of the electrons in an atom. For example, we know of the existence of large clouds of atomic hydrogen through a spin flip of an electron in a hydrogen atom, which occurs at a wavelength of 21 cm in the radio regime of the spectrum. The most common way that we are able to see giant molecular clouds is through rotations of carbon monoxide (CO) molecules that we observe through spectral lines. Warm ionized gas that is found near massive stars, on the outskirts of a galactic disk, and in the vicinity of massive black holes, emits spectral transitions of hydrogen at optical/visible wavelengths. At long infrared wavelengths, interstellar clouds emit a surplus of emission from a transition in carbon. As technology improves, we uncover fainter and fainter signals and construct telescopes that observe at wavelengths of the electromagnetic spectrum that were previously too complicated or costly to pursue.

Faint spectral signatures that I observe (and have observed for the first time in a distant galaxy, Chapter 4) are called **radio recombination lines** (RRLs). Radio recombination lines occur when an ionized atom (in the case of hydrogen, a proton) and an electron recombine. In some cases, the electron ends up in a high energy state after recombination, and from there it cascades down to lower energy levels. The steps down this cascade have very low and well-defined energies and are thus observable at specific wavelengths in the radio regime of the spectrum. The former makes them appear as "lines" in a spectrum and the latter puts the "radio" in radio recombination lines. While optical and infrared lines may be attenuated and scattered by dust, these spectral lines at radio wavelengths make it out of the medium unattenuated. Although they are faint and harder to detect, they are especially useful to infer the presence of massive stars towards obscured lines of sight (e.g., along the plane of the Galaxy) and in the dense environments of young star-forming regions.

In low-density gas, as a freshly recombined electron cascades down the energy levels of the atom, radio light and collisions with free electrons influence the cascading process. How effective those two processes can be during the cascade process and at which energy levels of the atom they occur are very sensitive to physical properties (temperature and density) of the diffuse gas. We observe the radio recombination lines at different frequencies, measure how the intensity changes, and use that to determine the temperature, density, and size of the gas clouds. When we measure the physical conditions, we can then quantify the influence of the different mechanisms which may be heating/cooling, pushing, diffusing, or stirring up the gas. Measuring these physical conditions using other means is usually not as direct, so observations of radio recombination lines provide a powerful complementary method for studying the interstellar medium.

I use a newly-constructed radio telescope, the **Low Frequency Array** (LOFAR),

to observe continuum emission and radio recombination line emission. LOFAR is centered in and operated from the Netherlands, but it also has stations in nine European countries. LOFAR was designed to observe at radio wavelengths of 1 – 30 m (3 – 100 feet!) or frequencies of 10 – 250 MHz, with a gap between 90 – 110 MHz straddling the FM Radio that we tune to in our cars and homes. These are the lowest frequencies that make it in and out of the atmosphere, as radio waves longer than about 30 m (10 MHz) are only reflected off the atmosphere. Radio waves increasingly closer to the cutoff frequency get distorted (refracted and rotated in polarization) as they pass through the atmosphere. Specifically, the layer responsible for this is called the ionosphere, and the distorting effects vary in time and location across the sky.

LOFAR is (one of a few of) a new generation radio interferometer and is enabling observations at these frequencies with high resolution and high sensitivity for the first time. Interferometers contain multiple antennas that can be used in conjunction to observe an astronomical object. Instead of having one gigantic telescope, a virtual telescope is created by harmonizing the signals from the antennas. LOFAR makes use of very simple antennas — there are actually two types for the two different wavelength ranges. Essentially, they are four pieces of metal (or wire) made with a specific length such that when radio waves of the desired length reach it, the radio light induces current in the antennas. Astronomers synthesize the read-out of the current to create images. LOFAR's antennas are inexpensive, and many of them can be installed to build up sensitivity and collecting area. Traditionally, steerable dishes have been used to point at a specific location in the sky. The LOFAR telescope is digitally pointed by imprinting the expected time delay observed across the telescope for a specific location in the sky. This antenna design also enables large patches of the sky to be observed simultaneously — for example, an area on the sky is observed simultaneously that equals 38 moons (the largest apparent size of moon) at the highest frequencies and an area of more than 2800 moons at the lowest frequencies!

Another telescope I use is called the **Atacama Large Millimeter/Submillimeter Array** (ALMA), located in Chile. Also recently constructed (at least it was at the start of my PhD program) in 2013, it has enabled high resolution and very sensitive observations at mm (and sub-mm) wavelengths for the first time. There are many molecular and atomic transitions that can be observed at these wavelengths, providing new ways to probe astrophysical properties through astrochemistry. ALMA is also an interferometer, but it is comprised of radio dishes with instruments that capture light with wavelengths of 0.8 – 3.5 mm. It is the largest observatory of its kind operating at these wavelengths — additional antennas achieve a better resolution and sensitivity.

What did I research in this thesis?

In my research throughout the PhD program, I investigated interstellar clouds on the scales of galaxies down to sub-cloud scales. I observed radio continuum emission from low-density ionized gas in a star forming region in our Galaxy, Cygnus X (remember the bubbling cauldron from Figure 5.23?) and studied the influence of massive stars through their transport of ionizing photons. I revealed the presence of a population of

rare super-star clusters in nearby galaxy and characterized their properties. I explored using radio recombination lines to observe galaxies at cosmological distances (very far away and young), and I developed the tools and strategies needed to process new low-frequency observations. While I lead these efforts, this research was carried out with the help and input from a host of collaborators and team members and through the guidance of my advisors.

In Chapter 1 of this thesis, I give an introduction (in more detail, for astronomers) to frame the concepts that we investigated. The research questions that are addressed in additional chapters:

- *Chapter 2:* How does low-density ionized gas affect the evolution of the massive, galactic star-forming region, Cygnus X? Are the same fingerprints present in surveys of low-density ionized gas in our Galaxy?
- *Chapter 3:* What are the properties of star formation (star clusters) in the central starburst of the galaxy NGC 4945?
- *Chapter 4:* Can the ISM be explored outside of the local universe through radio recombination line observations? What are the properties of the interstellar medium in a dwarf-like galaxy at $z = 1.1$?
- *Chapter 5:* What techniques are best suited to detect faint radio recombination lines (at an unknown redshift) in extragalactic sources?

What are the next steps?

So much is waiting to be discovered by building off of the research in this thesis. The analysis we present in *Chapter 2* — the thermal radio continuum from a star forming region in our Galaxy — is the first of its kind using the LOFAR telescope; roughly half of the galactic plane is observable by LOFAR and additional observations will statistically inform on the presence and origins of this plentiful gas phase of the interstellar medium. Furthermore, this work lays the foundation for LOFAR observations of radio recombination lines from diffuse molecular clouds and ionized gas in the Cygnus X region. By uncovering the presence of a rare population of super star clusters and characterizing their basic properties in *Chapter 3*, this work provides a valuable data set to investigate (i) stellar feedback and the influence of the star clusters on the medium, (ii) the early forming stages in the evolution of these types of star clusters, (iii) how many clusters of a given mass form and what influences that hierarchy, (iv) how cluster properties relate to their interstellar medium, and (v) a broader view is that these observations can be used in conjunction with the super star clusters in other nearby galaxies to potentially inform on the types of star forming conditions that were more common when galaxies in the universe were collectively peaking in the amount of stars forming. Observations with ALMA are only just starting to uncover these star clusters and the insights into our Universe that they provide. A major take away from this thesis, and *Chapters 4 and 5* in particular, is that the physical conditions in the diffuse interstellar medium can be explored through observations of radio recombination lines in and/or against radio-bright galaxies out to vast distances. This opens the door to investigations with existing facilities like the LOFAR,

VLA, GMRT, WSRT, MeerKAT, and ASKAP. On-going surveys that are searching for atomic hydrogen 21 cm emission in populations of galaxies are great complements and can be used to make more detections of radio recombination lines. The longer arcing future is rather bright because a new telescope which is just breaking ground on construction, the Square Kilometer Array (SKA), will enable significantly-more-sensitive observations at low radio frequencies and will revolutionize (extragalactic) radio recombination lines studies, allowing for the detection of (probe of) tens of thousands of sources.