

# Nearby Galaxies: Templates for Galaxies Across Cosmic Time

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# NEARBY GALAXIES: TEMPLATES FOR GALAXIES ACROSS COSMIC TIME

**Abstract:** Studies of nearby galaxies including the Milky Way have provided fundamental information on the evolution of structure in the Universe, the existence and nature of dark matter, the origin and evolution of galaxies, and the global features of star formation. Yet despite decades of work, many of the most basic aspects of galaxies and their environments remain a mystery. In this paper we describe some outstanding problems in this area and the ways in which large radio facilities will contribute to further progress.

## 1 Introduction

The nearby Universe offers us the products of cosmic evolution – galaxies – the archetypes for all objects elsewhere in the Universe. The Milky Way (MW) and our closest neighbors like the Magellanic Clouds provide the best data for understanding how a galaxy’s structure influences the ability of gas to form stars. Local galaxies can be used to derive star formation (SF) laws and to characterize the broad range of galaxy types, from ellipticals to irregulars, from spirals to active galaxies. Locally we can examine galaxy interactions and group and cluster influences. We can study nearby starbursts, HI supershells, and nuclear activity in detail. A knowledge of local galaxy parameters and their origin is critical to understanding objects at large redshifts, where we will require well-characterized templates of galaxies of all morphologies and Hubble types derived from studies of the nearby Universe.

Some key questions that motivate the study of nearby galaxies include

- **How did galaxies grow?**
- **What connects galactic structure and star formation?**
- **How do feedback processes affect galactic evolution?**
- **What is the origin and importance of magnetic fields?**
- **How are dark and baryonic matter related on the galactic scale?**

The image of the M81/M82 group shown in Fig. 1(left) illustrates the range of phenomena accessible for study in the nearby Universe: galaxy interactions, spiral structure, large-scale star formation, molecular clouds, group and cluster dynamics, and starbursts. In the coming decade study of nearby galaxies will remain a vital activity.

## 2 How do galaxies grow?

Cold dark matter plus dark energy (“ $\Lambda$ CDM”) models predict that galaxies are formed when baryons condense within dark matter halos, which in turn are connected via thin filaments: the cosmic web. The evolution of galaxies is driven by interactions and mergers, accretion of fresh gas, and feedback from stellar evolution. At every stage there are major gaps in our understanding.

Gas accretion, not only at early times but continuously to the present, appears to be indispensable given the chemistry and star formation history of today’s galaxies. In the local

Universe, obvious gas accretion mechanisms include minor and major mergers of galaxies, galaxy interactions, and flows from gas in galaxy halos or from the cosmic web. Our best hope of understanding the details of these processes is by observing them locally. By studying galaxy groups we can determine the rate and process of galaxy interactions and can delineate the history and future of galaxy mergers, e.g. the Magellanic Stream and the M81/M82 group HI trails. In nearby galaxies and the MW, high-velocity HI clouds may be evidence of current cool gas accretion [17]. Study of the cosmic web has its own set of questions: What is the metallicity of the web? Is there enough material and can it be transferred to galaxies efficiently enough to satisfy the chemistry model requirements? Does the local cosmic web behave like high- $z$  Ly-alpha absorbers? [2, 6]

### 3 What connects star formation to galaxy structure?

Today, the brightest stars form in spiral arms of galaxies. This simple observational result demonstrates the tight connection between galactic dynamics, which is largely determined by dark matter, and star formation. We know that compression and cooling of atomic gas leads to the formation of molecular clouds, but there are many gaps in our understanding of this process. On large scales, molecular clouds are embedded in the densest atomic gas reservoirs. On smaller scales, however, the simple correlation breaks down and the two gas phases are displaced from each other [13]. The location and mass of molecular clouds is thus not simply related to the distribution of the atomic phase; global as well as local effects are important for the formation of molecular clouds (see Fig. 1[right] of CO in M51).

The mass function of individual dense cores in a molecular cloud has a striking similarity to the initial mass function of stars, implying that the core mass function is somehow preserved throughout star formation, in spite of the small fraction of gas that is converted into stars (low star formation efficiency) and the very complex processes that are involved in the gravitational collapse of gas into a compact object [18, 1, 14]. An integrated way to express this property is the Kennicutt-Schmidt law. The study of local and global star formation processes is one of the major themes in the field of nearby galaxy research. Volume limited surveys of all galaxies within a distance of  $\sim 10$  Mpc are currently underway at many wavelengths (the Spitzer Local Volume Legacy [LVL] Survey, ANGST, VLA-ANGST, (Little) THINGS, 11HUGS, ATLAS<sup>3D</sup>, etc.), in a program to build up a statistically meaningful sample useful in deriving star formation laws and evolutionary pathways. The results of these surveys will provide the foundation for the interpretation of observations at higher redshifts and for understanding the evolution of star formation as a function of cosmic time.

### 4 Feedback processes in Galactic Evolution

Galaxy growth is not a one-way route. The accretion of gas onto galaxies provides the material for further star formation which ultimately produces massive stars, supernovae, and black holes, which in turn inject material and energy back into the surrounding ISM [19]. Feedback processes are indispensable elements of cosmic and galaxy evolution models along the Hubble sequence, however, feedback is one of the most poorly constrained parameters

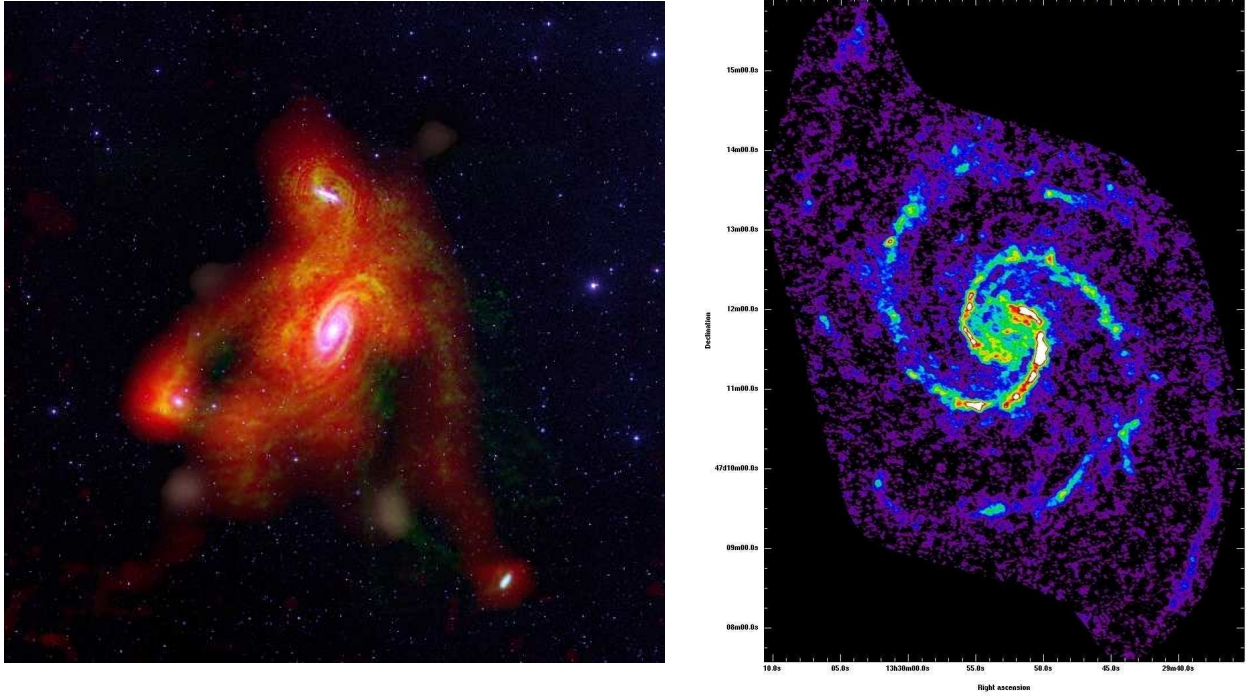


Figure 1: **Left:** THE M81/M82 GROUP AS OBSERVED IN HI WITH THE GBT AND THE VLA, SUPERIMPOSED ON AN OPTICAL IMAGE. THIS FIELD CONTAINS A RANGE OF GALAXY TYPES INCLUDING A STARBURST, EVIDENCE FOR STRONG INTERACTIONS, AND A FAIRLY NORMAL STAR-FORMING SPIRAL [5]. **Right:** CO(1-0) EMISSION FROM THE GALAXY M51 SHOWING THE SPIRAL PATTERN OF MOLECULAR CLOUDS [9].

in galaxy models. What governs the exchange of matter between a galactic disk and the intergalactic medium?

The most prominent examples of feedback are certainly the bright starburst and active galaxies such as M82 and Cen A. Depending on the gravitational potential of the host, however, lower level star formation across galactic disks could be even as effective in returning energy and metals to the IGM as nucleated starbursts. This effect is amplified by the sheer number of low mass galaxies. Other gas removal mechanisms include tidal interactions, ram pressure stripping, and galaxy harassment. Those less obvious, but possibly very important facets of feedback can be studied only in the nearby Universe. To understand distant starbursts we need templates from the local Universe (e.g., M82) for understanding the underlying mechanisms that drive, maintain, and terminate starburst events.

#### 4.1 Feedback from Star Formation

Energy and metals produced as the byproduct of stellar evolution are circulated throughout galaxies and into the intergalactic medium through phenomena such as jets, winds, superbubbles, and galactic fountains. The redistribution of matter and energy affects galactic and stellar evolution and may even modify the dark matter halo [11, 15]. A starburst can be strong enough to remove all gas thus stopping further SF processes. On the other hand,

density enhancements around SF regions may trigger further, secondary SF. A key question is if star formation must be initiated by large, galactic scale processes such as spiral arms and bars, or whether the turbulent ISM itself might trigger widespread, low-level SF. Episodic star formation is observed in many galaxies, often triggered by interactions. But is an interaction always required, or does the cooling of heated-up gas from former SF events determine the timescale for subsequent bursts and thus the episode timescales?

Each SF event injects large amounts of energy into the surrounding medium. Yet there are regions characterized by very high levels of star formation in a relatively small volume. How long can this be maintained? How are star-forming regions fed with gas without destroying them? Why are there large amounts of molecular gas adjacent to a region of extremely large ionizing flux, as occurs in starbursts? And finally, if starbursts can be maintained over a long period, how are they stopped? Is it pure starvation of feeding material or are there other mechanisms in place? Is there the equivalent of the Eddington luminosity limit for starbursts in nearby galaxies?

## 4.2 Feedback from Galactic Nuclei

During the last decade, an intriguing, almost linear, relationship was established between the bulge mass of galaxies and the mass of their central black hole [12]. This is surprising as the bulge is  $\sim 700$  times more massive than the central black hole and should dominate the system. Feedback processes from the black hole, however, might affect star formation in its surroundings and thus the bulge mass [16]. This feedback can be studied in great detail only in nearby galaxies. Active nuclei can produce large scale jets that influence interstellar and intergalactic space to Mpc scales. Jets may induce star formation or prevent star formation [7, 11]. In addition, AGN are frequently observed in conjunction with nucleated starbursts, sites of the most vigorous star formation activities in the Universe. The bi-conical winds produced by strong nuclear starbursts have a wider opening angle than jets and are able to remove larger quantities of gas, and importantly, carry freshly produced metals out of a galaxy. To understand the feedback from galactic nuclei and to study their influence on their environments in detail, it is indispensable to study nearby objects such as Cen A, M 82, NGC 253, Fornax A, or M 87 at high angular resolution and with sufficient sensitivity. In particular, the MW central black hole, Sgr A\*, provides a unique window into the connection between the massive central object and its immediate surroundings.

## 5 Molecules and Chemistry in the Local Universe

One of the major themes of radio astronomy has been the study of the interstellar medium (ISM), which breaks down into various phases at different temperatures, densities and ionization fractions. The chemical processes in the ISM produce a rich set of organic molecules, exotic species, and “pre-biotic” molecules that may be relevant to the origin of life on earth. For several decades molecules have been used as probes of interstellar processes, transforming our understanding of star formation and evolution, and the physical conditions in molecular clouds (e.g., [8]).

The coming decade will see increased activity in this area as well as a move to use astronomical observations to study chemistry itself. Terrestrial laboratories are largely limited to studying reactions in liquids or high-density gases. A question such as: *how does non-equilibrium chemistry proceed in a weakly ionized gas in the presence of magnetic fields?* crosses traditional disciplinary boundaries as it can be answered only by astronomical observations in conjunction with theoretical and laboratory studies.

Radio astronomy is a unique tool for fundamental chemistry. The lowest rotational transitions of molecules are in the centimeter to sub-millimeter wavelength range. The lines are weak and often from extended sources, so progress thusfar has been limited to study of only a handful of molecular clouds, almost entirely in the MW. In coming years, however, studies will be extended throughout the MW and to nearby galaxies as specific chemistry questions are asked that require probes of specific physical conditions.

## 6 The Origin and Importance of Magnetic Fields

Magnetic fields affect gas motions in galaxies and influence, perhaps control, the collapse of clouds into stars. They couple energy from supernovae to the interstellar medium. They control the density and distribution of cosmic rays. Yet the origin of the fields, their evolution, and many critical aspects of their interaction with gas remain controversial [21, 10, 3]. How are magnetic fields generated in galaxies? Is the field related to structure and dynamics of a galaxy? How do the magnetic fields (re)distribute cosmic rays and halo gas? Does reconnection provide an important heat source for a galaxy's disk and halo? How does the field evolve as a dense core contracts to become a star?

At the present time there are only a few galaxies that have good field measurements. What is needed is a much larger sample so that we can understand how magnetic structures derive from other galaxy properties. Zeeman splitting can provide the strength of the magnetic field in gas-rich regions of galaxies. Rotation measures of background sources will probe many sightlines and thus supply points in a grid on which to fit on large scale magnetic field models. Radio polarization sheds light on SN and SF dominated regions and events like galactic outflows.

## 7 Dark Matter

About one-quarter of the mass of the Universe is in the form of Dark Matter (DM), likely consisting of cold, non-baryonic particles. Outstanding questions include: What is the relationship between the baryonic and dark matter components? Are there "naked" dark-matter structures in galactic halos? Do nearby galaxies have the detailed structure implied by CDM models and where are the missing satellite galaxies CDM predicts? Are galactic warps coupled to the dark matter? What is the history of galaxy interactions in groups? What is the distribution of mass in the local group and what is the fate of the individual galaxies? A better characterization of the amount of DM on different size scales and how it is distributed is a critical need.

Astronomical observations can give considerable insight into the nature of DM: through precise astrometry we can determine the motion of nearby objects and deduce the local

gravitational potential. Gas motions in the Milky Way and other galaxies are sensitive to the potential on many size scales. We can trace the movements of large objects like galaxies in clusters. Studies of the structure of nearby galaxies have already confronted DM models with significant constraints [4]. This is an important and continuing activity.

## 8 Fundamental Science Opportunities

- **Extending “Galactic Astronomy” to a variety of galaxies**

With increased collecting area and spatial resolution, topics in “Galactic astronomy” will be studied in other galaxies. Subjects include the abundance and distribution of halo gas and HVCs; the details of star formation on the scale of individual pre-stellar cores; the relationship between atomic and molecular gas in SF regions; the distribution of objects like stars, pulsars, SNe and planetary nebulae, and their influence on the surrounding ISM. Currently this kind of science is restricted to the Milky Way (with some data from our closest neighbors like the Magellanic clouds) and is thus coupled to a specific type of galaxy with its very own evolutionary status and history. To perform these studies in a variety of galaxies – from dwarf irregulars to massive ellipticals, from isolated to interacting galaxies, from starbursting to ‘red and dead’ objects, from face-on to edge-on galaxies, from barred to AGN environments – will change our knowledge fundamentally. Some work on this has been done already, as shown in the figure of the M81/M82 group, and with some recent surveys like THINGS [20], but in combination with multi-wavelength studies in the optical, near-UV and infrared, the next generation of radio studies can characterize individual components of star formation in galaxies of very different morphology, size, and evolutionary state. Freed from observational restrictions that have confined much of our studies to the immediate Galactic neighborhood, we will derive vastly more accurate statistics on every aspect of star formation, galactic structure, and evolution.

- **The Chemistry of the Local Universe**

With increased sensitivity, radio astronomical observations will expand our understanding of basic chemical processes as they proceed under conditions not achievable in terrestrial laboratories, to yield fundamental information on the nature of the chemical bond. The use of chemistry as an astrophysical probe, and astronomy as a tool for chemistry, will provide unique opportunities for advancement of both fields.

## 9 Radio Instrumentation and Nearby Galaxies

Radio observations are unique in providing information on galactic gas in its ionized, neutral atomic and molecular phases over a range of conditions and angular scales. Radio observations are also unique in their ability to measure magnetic fields through Faraday rotation, the polarization of synchrotron emission, and the Zeeman effect in spectral lines. Only radio observations have the extremely high angular resolution necessary for the most precise astrometry. In addition, some of the most interesting regions (Infrared-dark clouds, galactic nuclei) are deeply obscured at optical and infrared wavelengths, and only radio observations provide access to the physics within.

- **Radio capabilities provided in the next decade**

EVLA<sup>1</sup> and GBT<sup>2</sup> observations of HI absorption against background sources may reveal cosmic web filaments in absorption along the line of sight, and, through Zeeman measurements, their magnetic field. GBT and EVLA studies of HI emission reveal the origin of HVCs, and their relation to Galactic structure, in the Milky Way and nearby Galaxies. Measurement of HI in fields around individual galaxies and in galaxy groups with the GBT and EVLA reveal signs of outflows and interactions and their history. The VLBA<sup>3</sup> is being used to derive Galactic structure to unprecedented accuracy, revising the mass of the Milky Way, and mapping the 3D velocity field of the local group through observations of proper motions of galaxies.

EVLA, GBT and ALMA can map the molecular clouds and cold dust in galaxies and galactic nuclei and determine their physical properties and kinematics. They can study chemical processes under conditions in the ISM that can not be replicated on Earth. The GBT is the only instrument that can observe the important CO(1-0) molecular line at essentially every redshift. Detailed studies of Sgr A\* with the EVLA and VLBA give information that can be applied to other nuclei. EVLA and GBT can measure magnetic fields in HI and OH through the Zeeman effect.

- **Enhancements needed to achieve the science goals**

The ultra-compact EVLA E array will provide sensitivity on angular scales needed to make initial studies of the cosmic web in 21cm or radio continuum emission. GBT focal plane cameras in the HI line will allow deep mapping of wide areas, and at 22 GHz will identify extragalactic water masers for local group proper motion studies. Focal plane cameras on the GBT will provide wide-field, high-sensitivity mapping of molecular clouds in many molecular lines at wavelengths as short as 3mm, providing great synergy with ALMA. EVLA E array will improve sensitivity to molecular emission on arc-min scales. Increased sensitivity of the VLBA and HSA will allow precise astrometry on faint objects, and more precise distances to star-forming regions.

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<sup>1</sup>Expanded Very Large Array <http://www.aoc.nrao.edu/evla>

<sup>2</sup>Robert C. Byrd Green Bank Telescope <http://www.gb.nrao.edu/gbt>

<sup>3</sup>Very Large Baseline Array <http://www.vlba.nrao.edu/>