# 4. Galaxies in the Local Universe

## 4.1 Introduction

The local universe provides a vital link between our Milky Way Galaxy and the early universe. In particular, the study of nearby galaxies provides crucial insights into the properties of our own Galaxy. For example, understanding the nature of the Milky Way's spiral structure is very difficult from our vantage point, immersed as we are within this disk. In contrast, one can investigate processes in nearby galaxies with high spatial resolution but without the foreground confusion that limits studies in the Milky Way. Moreover, by defining the current state of galactic evolution in nearby systems, we gain insight into the processes that drove evolution in the early universe.

## 4.2 Molecular Gas Distributions

The distribution and abundance of dense interstellar matter plays a critical role in determining the morphology and evolution of galaxies. Stars predominantly form in giant molecular clouds (GMC) with sizes of 10-50 parsec and masses ten thousand to a million times that of the Sun. The massive stars that emerge from these clouds emit much of the optical luminosity of a galaxy and are responsible for the chemical enrichment of the interstellar medium (ISM). These giant clouds are comprised mostly of molecular hydrogen, which does not readily radiate under typical interstellar conditions and is hence difficult to observe, so that GMCs are most frequently traced by spectral line radiation from carbon monoxide (CO) and the continuum emission from interstellar dust grains. The LMT is optimized to define the physical state of this cold, interstellar component of galaxies and its role in the star-formation process.

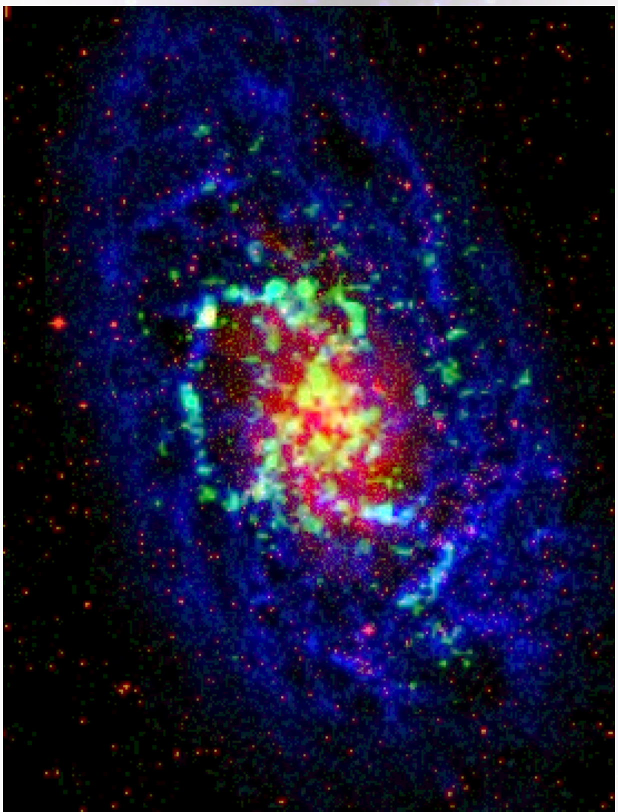

*Figure 4.1 The nearby galaxy M33, showing the optical emission (red), neutral hydrogen emission (blue), and CO emission (green; observed with SEQUOIA at FCRAO)[1].*

With unique millimeter-wave imaging instrumentation, the LMT will enhance our understanding of galaxies by imposing critical observational constraints on prevailing paradigms and discovering new phenomena to be explained by the models. The LMT's large diameter and high operating frequency will enable astronomers to accurately image complexes of molecular gas and dust that are current or future sites of star formation within the disks of galaxies, and, furthermore, to rapidly conduct unbiased surveys of the properties of these disks. For example, the angular resolution of the LMT corresponds to about 20 parsec at the distances of the Andromeda Galaxy (M31) and the Triangulum Galaxy (M33; Figure 4.1) sufficient to resolve individual giant molecular gas clouds. The LMT will hence be able to map the location and kinematics of dense molecular clouds in several hundred nearby spiral galaxies, and to study cloud formation and dissipation as they pass through the shock fronts within galactic spiral arms. Most of the LMT instruments are multi-pixel cameras, well suited for such rapid imaging studies, so that investigating a large number of galaxies in a systematic and statistically robust manner will finally become possible. Figure 4.2 demonstrates the capability of the LMT to relate the spatial and kinematic relationships of the molecular gas to the dynamical features in a galaxy, such as spiral arms, stellar bars, and nuclei.

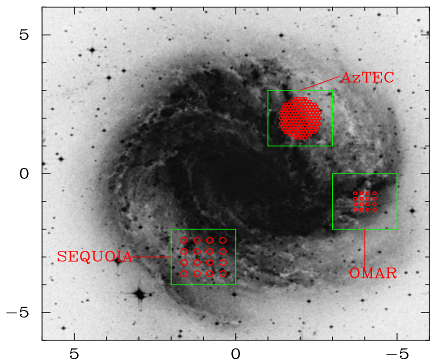


*Figure 4.2 An optical picture of the M83 galaxy[2] with footprints of the LMT focal plane arrays (see Chapter 8). These show the ability of the LMT to resolve the molecular gas and dust components with respect to spiral arms and sites of star formation in nearby galaxies. Scanning the telescope across the field will image the entire galaxy.*

## 4.3 Instabilities and Star Formation

The spatial coherence of OB stars and HII regions in galaxies attests to large-scale processes that regulate the formation of stars. Many earlier studies have demonstrated that the star formation rate in galaxies is ultimately limited by the formation of giant molecular clouds from the diffuse interstellar medium[3,4]. This necessary evolutionary step can be affected by pressure disturbances that drive warm neutral material into the cold, dense, molecular gas phase; such disturbances include global spiral density waves triggered by galactic mergers and interactions, disk instabilities and shells driven by supernovae at intermediate scales, and density fluctuations from compressible, turbulent gas flows at all scales. With its capability of imaging the molecular gas and dust components as proxies for molecular hydrogen, the LMT can define the spatial and kinematic relationships between the population of giant molecular clouds and the overlying atomic gas component most readily traced by the HI 21 cm transition. Such relationships can distinguish the most relevant factors responsible for the development of giant molecular clouds and the subsequent formation of stars in galaxies.

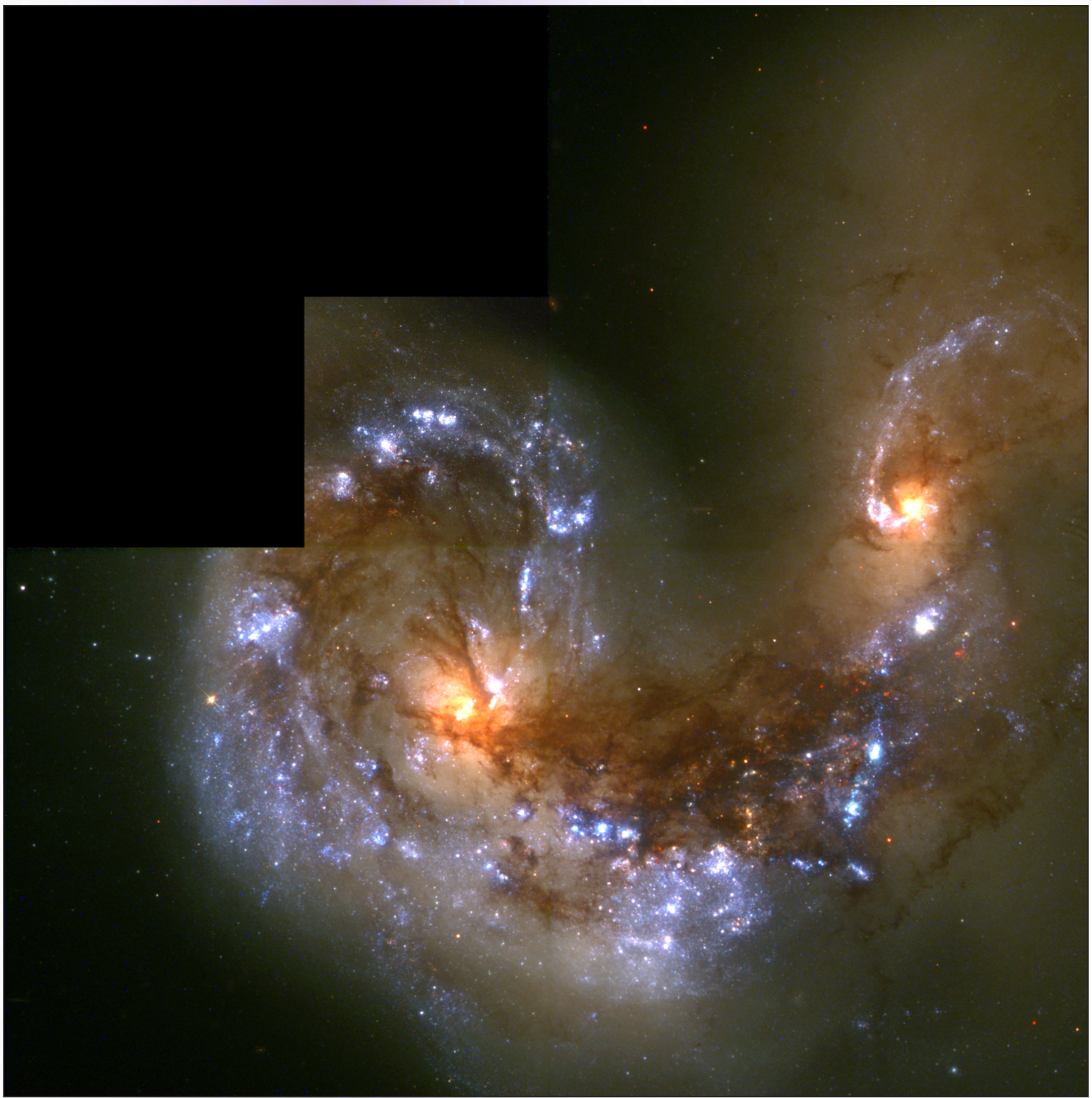

*Figure 4.3 Hubble Space Telescope image of the merging nuclei of the antennae galaxies NGC 4038 and NGC 4039[5]. This merger process is responsible for creating conditions favorable for the rapid, efficient conversion of molecular gas into stars. The LMT can provide important insight to this process by measuring the flow of molecular gas into the central regions.*

Starbursts galaxies constitute a class of objects in which the star-formation rate and efficiency is many times greater than values found for normal galaxies like the Milky Way. Such extreme systems within the local universe are plausible analogs for the luminous sub-mm and mm objects observed at high redshifts. The starburst phenomenon results from the rapid changes in the dynamics of interstellar material that remove angular momentum from the gas and trigger large-scale infall towards the central regions of a galaxy. The gas within the starburst nuclei is denser than that found in normal galaxies and more conducive to the formation of stars. Such dynamical calamities are caused by galaxy mergers, interactions, or strong, barred potentials. The infalling motions of the gas can be currently measured by mm-wave interferometers. However, to accurately quantify the amount of infalling molecular material, it is essential that a complete accounting of the gas be made with a filled aperture telescope like the LMT that can image the entire galaxy, inclusive of an extended, molecular gas component, with high angular resolution. Such measurements can provide pivotal information that can define the large-scale dynamics of such extreme systems of star formation.

A significant improvement in technical capability, such as the angular resolution and sensitivity that will be obtained with the LMT, not only allows scientists to solve old problems better, but often it also provides new scientific tools to tackle new problems. One such example enabled by the LMT is the use of hydrogen recombination lines as tracers to determine where young, massive stars are forming in galaxies and how many form per year. Because all young massive stars are born within a thick gas and dust cocoon, most of the light from such a young star is absorbed by dust and re-radiated in the infrared, and an indirect inference is normally made about the rate of star formation after measuring the infrared light. Hydrogen recombination lines at millimeter wavelengths originate from the gas surrounding the stars themselves that is ionized by the stellar ultraviolet radiation. Since the gas and dust cocoon surrounding the young star is transparent to light at millimeter wavelengths, hydrogen recombination lines observable by the LMT represent a more direct indicator of the activities associated with the formation of young massive stars. In addition, several nearly identical recombination transitions are found within the 3 mm and 1 mm wavelength windows, and the observational efficiency can be increased by several fold if these are observed simultaneously and summed.

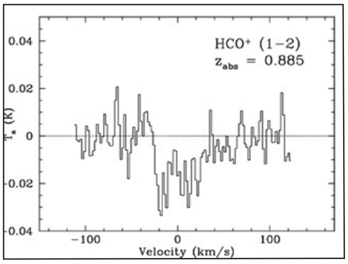


*Figure 4.4 The $z = 0.885$ $HCO^+$(1-2) absorption system detected toward the high redshift quasar PKS 1830-211 with the FCRAO 14 m telescope*[6].

## 4.4 Probing Physical Conditions in the Interstellar Medium

The rotational transitions of CO provide a useful tool to quantify the global properties of GMCs, but their use can be limited due to high line opacities and insensitivity to the high density ($>10^5$ cm$^{-3}$) zones within the cloud from which the stars ultimately condense. Surface densities of the gas within galaxies can be determined with fewer assumptions by imaging tracers of molecular hydrogen with lower optical depths, such as $^{13}$CO or the thermal dust continuum. In addition, astronomers can more accurately quantify the dense gas conditions with observations of multiple transitions of a given molecule, including molecules that more directly probe higher densities, such as HCN, $HCO^+$, and CS. These more diagnostic observations are difficult because the lines are inherently weaker and the filling

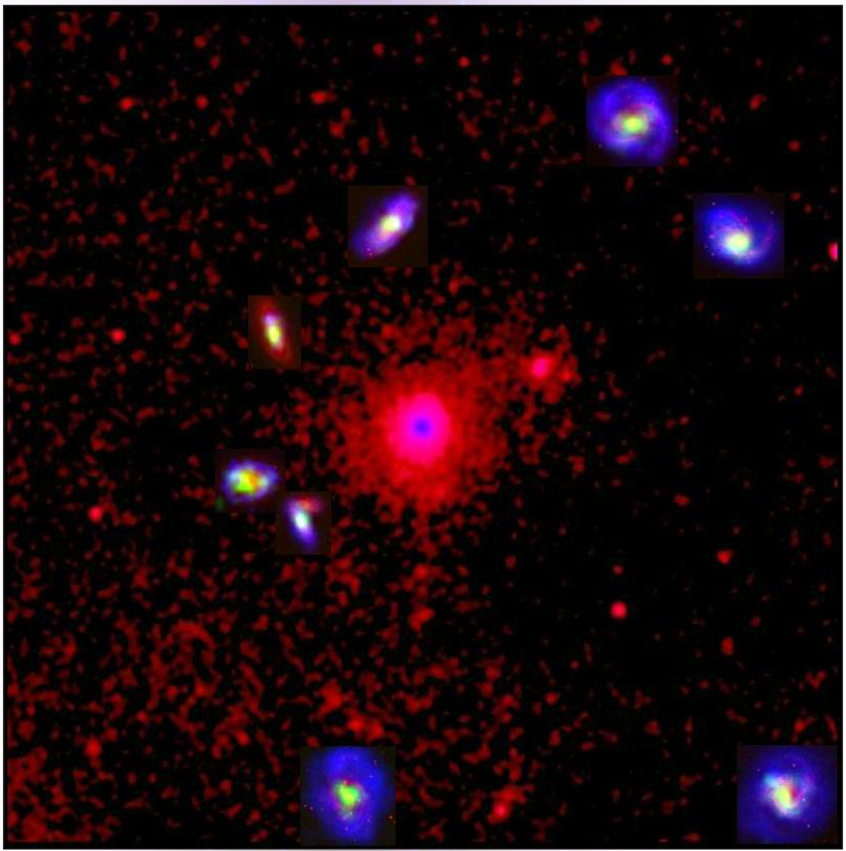

*Figure 4.5 Color composite images of nine Virgo cluster galaxies (CO in green, HI in blue, and optical, inside individual galaxy images, in red). The CO emission has been imaged using the SEQUOIA array on the FCRAO 14 m telescope[8]. Positions of the individual galaxies with respect to the X-ray emission in the cluster (ROSAT soft X-ray image, shown in red and magenta) are largely accurate, but the images of the individual galaxies are magnified by a factor of seven to show the morphological details better.*

factors may be small, further weakening the signal to be measured. In these cases, a large collecting area of the telescope system is essential. With its powerful suite of imaging instruments and a collecting area exceeded only by the future ALMA, the LMT can conduct such observations to investigate the variation of molecular gas conditions as a function of radial position within a galaxy. These conditions can be directly compared to local star formation rates and efficiencies to assess the regulatory processes within galaxies.

The sensitivity achieved by the large collecting area and the precision surface of the LMT offers another unique tool for probing physical conditions in the interstellar medium of the more distant galaxies. For many years optical and ultraviolet astronomers have successfully exploited the absorption of light from distant bright sources passing through foreground gas clouds to learn about the nature of the warm and hot gas within and surrounding galaxies. In principle, the same technique can be used at mm wavelengths to study the nature of the cold ISM in galaxies along the lines-of-sight.

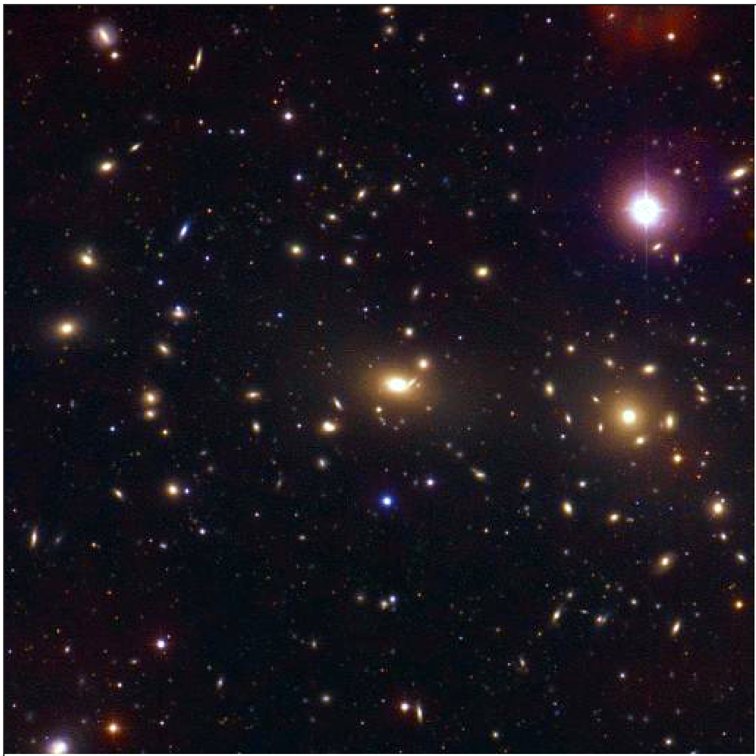

*Figure 4.6 A color picture of the inner region of the Coma Cluster[9]. Hundreds of galaxies in clusters like this can be imaged and studied simultaneously using the LMT.*

In fact, a handful of absorption systems have already been identified and studied at mm wavelengths (see Figure 4.4 for an example). However, the number of background sources bright enough for such absorption studies using existing mm-wavelength telescopes is small. Moreover, all existing telescopes have extremely limited instantaneous frequency coverage, making searches for absorption lines in the frequency domain extremely inefficient. The high sensitivity of the LMT increases the number of available target sources to several thousands, and the frequency agility of the LMT instruments is extremely well suited for absorption system searches and detailed follow-up investigations. When a large number of molecular transitions are detected in several systems spanning a wide range of redshifts (distances), interesting insights on variations in physical properties of the ISM, such as gas density, temperature, and chemical abundances, can be obtained. In addition, such general properties of the universe as the *in situ* cosmic microwave background temperature and the value of fundamental atomic constants can be explored.

## 4.5 Large Imaging Surveys of Nearby Galaxies

In cosmological models of the universe dominated by cold dark matter (CDM), galaxies form and evolve in denser regions through gravitational collapse and subsequent growth. In these models, galaxies grow larger and more massive by a series of mergers and acquisitions of smaller galaxies and gas clouds from their surroundings. Therefore, environment plays a critical role in the mass growth and star-formation history, as well as the future fate, of all galaxies. In their pioneering and yet unsurpassed work, Young et al.[7] measured CO (1-0) emission in over 300 galaxies using the FCRAO 14 m telescope to characterize the molecular gas content in galaxies of different Hubble types. Because of observational limitations, only scans along the major axis or frequently the total line flux from a galaxy could be obtained, so that usually only the global gas properties could be derived. In contrast, investigation of the dependence on environment of gas distribution (Section 4.2), disk kinematics and star-formation (Section 4.3), and physical conditions of the ISM (Section 4.4) require spatially resolved complete mapping of gas tracers and gas kinematics.

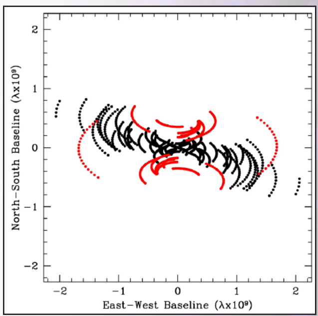


*Figure 4.7 Baseline coverage for 86 GHz VLBI observations of the Galactic Center using the VLBA and the LMT[12]. As more of this plane is filled in, the images of astronomical sources become more accurate and are more rapidly obtained. VLBA-only baselines are shown in black, baselines to the LMT are shown in red. The LMT provides critical North-South coverage to enable sensitive searches for extended intrinsic structure, as well as multiplying the sensitivity of the entire array by over a factor of two.*

The critical importance of galaxy environment and spatially resolved imaging of molecular gas is dramatically demonstrated by the CO imaging survey of large spiral galaxies in the Virgo cluster using the FCRAO 14 m telescope. As shown in Figure 4.5, the spatial extent of cold gas in these disk galaxies is substantially truncated for galaxies closer to the cluster center as traced by X-ray emission, indicating that the presence of an intercluster medium and high galaxy density have an immediate impact on the ISM content of individual galaxies, which in turn will affect the current and future star formation activities. Another CO imaging survey of the largest angular size galaxies targeted by the Spitzer Infrared Nearby Galaxies Survey (SINGS) is currently under way at the FCRAO.

Taking advantage of the high angular resolution and fast mapping speed of the LMT, astronomers at UMass Amherst and INAOE will conduct imaging surveys of molecular gas tracers such as CO for a large sample of nearby galaxies representing different galactic environments, as in the Coma cluster. Comparisons of CO emission with the HI and Spitzer infrared images should reveal the relationship between the large scale cold gas and stellar structures, the gas distribution, and star formation activity. During the first few years of operation the LMT will image CO emission in hundreds of galaxies with sub-kiloparsec spatial resolution out to a distance of 100 megaparsecs. Spatially resolved analysis of gas and dust properties in statistically significant large samples of diverse Hubble types and environments will be conducted using these data.

## 4.6 Exploring the Galaxy with VLBI

Inclusion of the LMT in various global Very Long Baseline Interferometry (VLBI) networks offers the opportunity to achieve unparalleled angular resolution (Section 2.4.4) and, consequently, to attack fundamental astrophysical problems in new ways (Figure 4.7).

### 4.6.1 Imaging a Black Hole Event Horizon

Perhaps the single most promising and important project that an LMT-anchored VLBI array would achieve is establishing the existence and nature of the massive black hole in the center of the Milky Way. It is now generally accepted that the central energy source in AGNs is accretion onto a massive black hole (MBH), since energy output and size limits preclude most other phenomena. Yet, for such a widely accepted theory, our detailed understanding of processes and physical conditions on scales of a few Schwarzschild radii ($R_{sch}$) near the black hole event horizon remains limited.

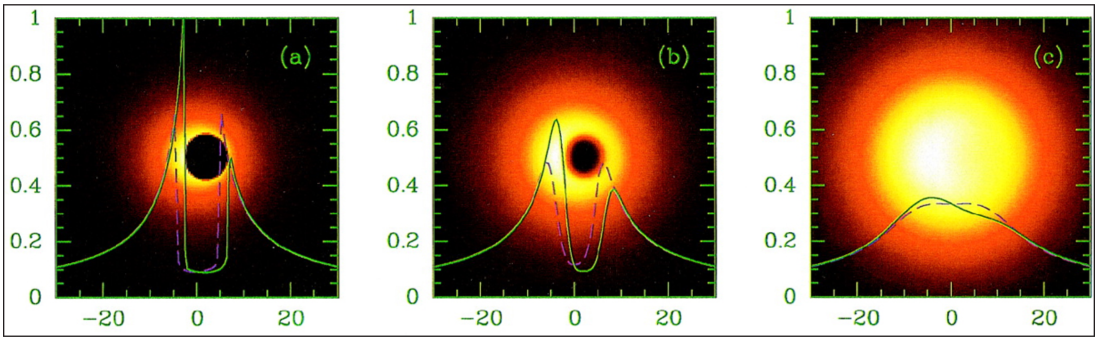


*Figure 4.8 Images of optically thin emission surrounding a rotating SgrA*-mass black hole with radiating gas in free fall[13]. Panel (a) shows results of general relativistic ray tracing calculations, (b) shows what a 450 GHz VLBI array would see with both scattering and beam size incorporated, and (c) shows the emission as seen by a 230 GHz VLBI array with scattering and beam size effects. Dotted and solid lines show horizontal and vertical intensity cuts through the images with the y-axis in relative intensity units. The x-axis is in units of the gravitational radius of the black hole (0.5 x $R_{sch}$).*

VLBI can be used to study AGN on size scales commensurate with the most compact regions near the central singularity. The best prospect for studying an AGN with linear resolutions of a few $R_{sch}$ is, in fact, SgrA*, the compact radio source at the center of our Galaxy. The case for linking SgrA* with emission from an approximately 4 million solar-mass black hole at the center of the Galaxy is now quite strong. High-velocity spectra of stars near the Galactic center and observed orbits of these same stars[10] indicate an enclosed mass of this magnitude. Upper limits on the proper motion of Sgr A* itself show that the radio source must be associated with at least 400,000 solar masses. These mass estimates, combined with

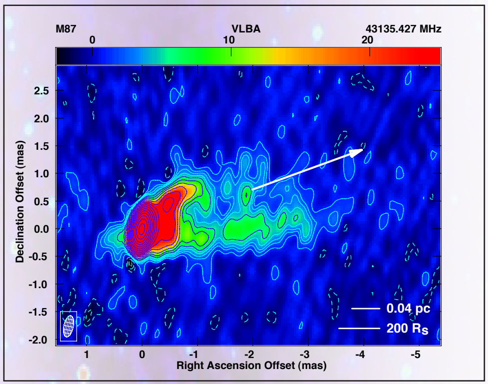


*Figure 4.9 VLBA image of M87 at 43 GHz[15]. Jet emission is clearly detected from 0.5 out to 3 milli-arcseconds (140 –820 $R_{sch}$ for the 3 billion solar mass black hole thought to be powering this AGN) along the direction of the larger kiloparsec-scale jet indicated by the arrow. Future high sensitivity 86 GHz and 230 GHz VLBI arrays, which include the LMT, will boost the linear resolution on this source to 10 - 25 $R_{sch}$ .*

intrinsic sizes measured using VLBI at 43 GHz and 86 GHz[11] imply mass densities in excess of 2000 trillion trillion ($2 \times 10^{21}$) solar masses per cubic parsec, or about four orders of magnitude smaller than the density of a 4 million solar-mass black hole. Since any conceivable aggregation of matter with this density would coalesce into a black hole on time scales short compared to the age of the Galaxy, this result is the best evidence to date for the existence of massive black holes. It is not, however, conclusive proof—for that one requires direct observations of either relativistic motions at the event horizon, or other strong general relativistic signatures of a gravitational singularity.

The ionized ISM scatters and broadens radio images of SgrA* with a dependence on wavelength squared, making VLBI at the highest frequencies (shortest wavelengths) the only available means to set important limits on the intrinsic structure and size of SgrA*. In the 86–230 GHz band, one can use the LMT in VLBI arrays to carry out observations that will probe emission mechanisms and structures within a few Schwarzschild radii of the event horizon. At 86 GHz, the increase in sensitivity provided by the LMT, coupled with the important North-South baselines it provides to the VLBA, will allow tests for asymmetries in the intrinsic structure of SgrA* on 6-10 $R_{sch}$ scales. Such asymmetries are predicted by jet models in which the SgrA* emission is produced in an outflow of relativistic particles, analogous to larger extragalactic AGN. The time scales of SgrA* X-ray and IR flares correspond to light crossing times of 10's of $R_{sch}$, with the intriguing possibility of observing a structural change *during* a VLBI observation.

At 230 GHz the angular resolutions provided by LMT baselines to antennas on Hawaii and in South America are sufficient to begin searching for strong general relativistic effects predicted in the immediate vicinity of the black hole at the Galactic Center. A true black hole embedded within an optically thin accretion flow should appear with a central dimple or 'shadow' (Figure 4.8). This 'shadow' morphology requires existence of a true singularity, and models show that sensitive VLBI arrays operating at 230 GHz and 450 GHz should be sensitive to this unique feature[13]. SgrA* would then become a unique test case for general relativity theory and detailed mechanisms of matter inflow and energy output surrounding a black hole. Successful observations would also mark the end of the Massive Black Hole scenario as a paradigm and its emergence as a fundamental reality in physics.

#### 4.6.2 Cosmic Accelerators: How AGN Launch and Collimate Relativistic Jets

A long-standing question in astrophysics is how central engines in AGN accelerate and then collimate jets of relativistic particles. VLBI observations of superluminal motion in these jets confirm that the bulk particle flow in numerous cases must be very close to the speed of light (0.98c in the case of the Seyfert galaxy 3C120). VLBI at the highest resolutions is required to image the base of these flows, and high frequency observations are needed not only to penetrate the optically thick radio cores of these sources, but also to avoid Faraday depolarization effects, which mask magnetic field structures at lower frequencies. A Global VLBI array observing at 43 GHz has already shown that the jet of M87 (Virgo A) has a broad opening angle within ~100 $R_{sch}$ of the central black hole, implying that the jet collimation is governed by the accretion disk and not processes near the black hole[14]. These same observations also show limb-brightening along the sides of the jet base, strengthening arguments for magnetic collimation. New 86/230 GHz VLBI arrays including the LMT and making use of high bandwidth VLBI recording systems will reach linear resolutions of 10-25 $R_{sch}$ for M87, enabling tests of MHD acceleration mechanisms on size scales commensurate with the accretion disk. Equally important will be high-frequency polarimetric observations using these arrays, which will measure magnetic fields at the very beginnings of the collimation process. Other sources, including 3C120, can be studied with similar linear resolutions.

### 4.7 References

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