Molecular gas in spiral galaxies

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1 Abstract:

In this review, I highlight a number of recent surveys of molecular gas in nearby spiral galaxies. Through such surveys, more complete observations of the distribution and kinematics of molecular gas have become available for galaxies with a wider range of properties (e.g., brightness, Hubble type, strength of spiral or bar structure). These studies show the promise of both interferometers and single-dish telescopes in advancing our general understanding of molecular gas in spiral galaxies. In particular, I highlight the contributions of the recent BIMA Survey of Nearby Galaxies (SONG).

2 Introduction

Molecular gas is arguably one of the most important constituents to consider in any study of galaxy evolution. It is the raw material from which stars form, and it responds strongly to dynamical influences which can move large amounts of gas. Spiral galaxies, in particular, provide a variety of environments in which to study the processing of molecular gas. For instance, galactic bars are likely important in fueling central star formation by promoting the flow of gas inward. The star formation resulting from the influx of gas may in turn promote the development of a bulge-like structure, or even the destruction of the bar itself (e.g.,[1],[2],[3]). In addition, the presence of a bar or spiral potential may influence the large-scale pattern of gas, and therefore new star formation (e.g.,[4],[5],[6]).

The symmetry of the H_2 molecule effectively limits the direct detection of molecular material to the small fraction of warm molecular gas typically found in the vicinity of shocks or star formation. Due to its relatively high abundance and low effective excitation, the CO molecule has become a standard proxy for H_2, and its emission (particularly from the J=1-0 transition) has been detected in many galaxies, in some cases out to very large redshift (e.g., z=6.419,[7]). There is still significant debate about the appropriate conversion factor between CO integrated intensities and H_2 surface densities in different environments (see presentations by M. Guelin, F. Walter, and A. Bolatto in this volume; see also, e.g., [8],[9],[10],[11],[12]). However, there is no

question that CO observations play a key role in discovering the whereabouts and motions of molecular gas in galaxies outside the Milky Way.

In the last decade, the improved sensitivity of millimeter-wave facilities has enabled studies of the distribution and kinematics of molecular gas in galaxies on smaller spatial scales, at larger radii, and over smaller velocity shifts. In particular, the advent of a number of surveys has significantly advanced the study of molecular gas in nearby galaxies since the previous Zermatt Symposium. We now have a full accounting of the molecular gas in Local Group spirals, as well as a self-consistent accounting of the detailed molecular gas distributions in wider samples of Hubble type, bar contribution, and star formation activity. For the purposes of this presentation, I include techniques such as On The Fly (OTF) mapping (with single-dish telescopes) and mosaicking (for interferometers) as "survey" techniques.

3 Surveys of Local Group Spirals

In the disks of our nearest spiral neighbors, M31 and M33, we can resolve populations and kinematics of Galactic giant molecular cloud (GMC) analogs. Their proximity also requires on the order of 1000 pointings for a typical millimeter telescope or interferometer to cover the angular size subtended by the star-forming disk. Therefore, complete studies of these individual galaxies can rightly be called surveys, and they provide the means to study cloud populations in external galaxies in an unbiased way.

3.1 M31

M31 is the nearest spiral to our own, offering an alternative view of a large, bright spiral galaxy. The large inclination of M31 motivates the study of molecular gas at high angular resolution, in order to separate arm and inter-arm regions and assess the properties and development of spiral structure. Recent efforts to attain a complete assessment of the molecular gas in M31 have seen a dramatic improvement in spatial resolution, from the first complete CO survey at 1.7 kpc resolution in 1993 (with the CfA 1.2m,[13]) to a higher resolution (200 pc) survey of the southwestern half of the galaxy (with the FCRAO 14m, [14],[15]) and a full survey at better than 90pc resolution (with the IRAM 30m,[16]) in the last few years. We can now assess the properties of the spiral structure and molecular cloud population in M31, and compare it with those of the Milky Way (see presentation by M. Guelin, this volume). Furthermore, the wealth of kinematic information over a wide range of radii can be used to constrain galaxy properties such as the shape and rotation speed of the bulge [17],[18].

3.2 M33

M33 offers a contrasting view of the properties of a nearby, later-type spiral. After a seminal study of the properties of molecular gas in the nuclear region of M33 [19],[20], it has taken a decade to expand on this important work. The recently completed 759-field survey covering the star-forming disk of M33 at 50 pc resolution (with BIMA, [21]) is the first flux-limited sample of distinguishable GMCs in a spiral galaxy, and creates a database of 148 GMCs with which to study the properties of molecular clouds in M33. In turn, it has enabled a higher resolution (20 pc) study of a high-mass sample of giant molecular clouds in M33 [22]. These studies confirm that M33 seems to be devoid of the most massive GMCs seen in the Galaxy, and enable comparisons with other tracers such as HI and Hα which can be used to constrain GMC lifetimes, a gas depletion timescale, and cloud formation mechanisms.

4 Surveys outside the Local Group

As we leave the Local Group, we return to the more traditional definition of a survey, that of studying many different objects rather than many pointings on a single object. Through surveys, we are rapidly gathering enough information on molecular gas in spiral galaxies to begin making general statements directly from statistical samples.

4.1 Single-dish Surveys

Much of our basic understanding of the global properties of gas distributions in spirals come from single dish surveys. Single dish telescopes are able to observe a significant fraction of a galaxy in a single beam, and do not suffer the uncertainties of missing large-scale flux inherent in interferometer studies. The groundwork for our understanding of the molecular gas content of spiral galaxies was laid by earlier surveys (e.g.,[23],[24],[25],to name a few), which indicated that molecular gas can be detected over a range of Hubble types, and tends to be more enhanced in the centers of galaxies than in the outskirts. Further, we find that molecular gas and star formation tracers are generally closely associated, though interpretations of the form of this association vary (e.g., [26],[27],[28],[29]).

Recent single-dish surveys (e.g., [30], [31], [32], [33], [34],[35]) highlight the fact that virtually all single-dish millimeter telescopes are actively engaged in surveys of a wider range of molecular gas properties in spirals. In recent years, these and other studies have been used to improve our measures of molecular gas in very late type spirals (Scd-Sm), construct higher resolution central rotation curves than are available from HI, and show the promise of mapping variations in molecular gas excitation and density through observations of higher rotational transitions of CO.

Single-dish telescopes have also been used increasingly in a mapping mode such as On-The-Fly (OTF) mapping. Rather that measuring only the central surface density or the variation of surface density along the major or minor axis, these studies map the detailed variation of the emission from various parts of the galaxy. An excellent example is the fully-sampled mapping of 5 nearby spiral galaxies with the NRAO 12m (now the UASO 12m), including IC 342 and M83 ([36],[37],[38]). These single dish studies discern individual arm and interarm regions, and can trace the relationship of molecular and atomic gas in detail. These studies show smooth connections between the molecular and atomic gas components, which suggests that the gas phase may be determined by local variations in turbulent pressure or dynamical conditions (e.g., [39], [40],[41], [42], [43], [44]).

4.2 Interferometric Surveys

Large single-dish telescopes such as the IRAM 30m and the Nobeyama 45m can achieve moderate angular resolutions of $\sim$10-20$''$, corresponding to $\sim$1-2 kpc at d=20 Mpc. Therefore, achieving kiloparsec or even sub-kiloparsec resolution in a large number of nearby spirals requires the use of interferometers. The observations possible with current millimeter interferometers provide important information for planning future surveys with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) and the Atacama Large Millimeter Array (ALMA).

Circumnuclear Molecular Gas

With significantly higher resolution, interferometric studies are well suited to study central molecular gas properties, and their relationship with central activity. The progress of one of the most recent such surveys, The NUclei of GAlaxies project (NUGA), has been reported at this meeting by S. Garcia-Burillo and L. Tacconi. A study with the NRO and OVRO interferometers of CO emission in 10 barred and 10 unbarred spirals [45],[46] reveals that molecular gas is more concentrated in barred than unbarred spiral galaxies, thus providing the first statistical evidence for bar-induced inflow in transporting gas to the centers of galaxies. However, this study found no correlation between central gas concentration and type of nuclear activity, which may indicate that the resolution of the survey (4$''$) was not sufficient to assess separately the properties of the circumnuclear gas.

Recent dissertation projects by S. Jogee [47] and A. Baker [48], as well as the OVRO MAIN survey (see description in [49],[50]) complement these studies by targeting particular aspects of the interaction of molecular gas with other activities in the centers of galaxies. Jogee compared central molecular gas mass and central star formation activity, and showed that information about gas kinematics as well as the size of the gas reservoir was necessary to determine whether or not a central starburst would form. The Baker study

of molecular gas in AGN with broad Hα line emission, as well as the OVRO MAIN multi-line survey, are being used to study central kinematic and heating conditions, and to test which processes are most influential in determining central activity in galaxies.

The Nobeyama Millimeter Array (NMA) has been used recently to target spirals in the Virgo cluster, using the advantage of a common distance to minimize ambiguities when comparing structures between galaxies ([51],[52],[53]), thus being able to compare directly the inferred surface mass densities and effects of interactions on molecular gas distribution and motions.

Gas in Disks

The interferometric surveys described thus far have included CO brightness as a criterion for selection into the study. Such studies may be biased by an unknown factor toward galaxies with more significant, or more highly concentrated, molecular gas masses. The BIMA Survey of Nearby Galaxies, or SONG, is the first large interferometric CO survey to observe galaxies which were not chosen on the basis of central CO brightness [54],[55]. The 44 spirals in SONG were chosen by the following criteria: Hubble type Sa-Sd, $V_{sys} < 2000$ km s^{-1}, $i < 70^o$, $\delta > -20^o$, and B$_T$ <11.0[1]. Observations for SONG effectively mapped a $\sim$10-kpc diameter region around each galaxy center, enabling a more accurate assessment of the properties of gas in the inner disk. CO J=1-0 emission was detected in 41 of the 44 chosen galaxies (within a radius of 120$''$), providing a broad sample of galaxies with which to explore the properties of gas and star formation over a range of radii [2].

The BIMA SONG data (see Figure 1) show that the molecular gas distributions in spiral galaxies are very heterogeneous, and even the azimuthally averaged radial profiles show a range of properties with respect to the radial variation of the stellar light. A comparison of the molecular gas distributions in barred (SB/SAB) and unbarred (SA) galaxies in the full SONG sample [56] confirms and strengthens the results of the NMA-OVRO survey: the average central gas surface density of barred spirals is three times higher than that of unbarred galaxies. It also appears that in many spirals the increase in molecular gas surface density occurs over the same range of radii in which the stellar light increases above that of an exponential profile [54],[57]. As this central "excess" occurs commonly in unbarred galaxies as well as barred galaxies, there may be some other mechanism than bar inflow required to explain central gas excesses in all spiral types. The complete coverage of molecular gas in the inner disk has enabled detailed studies of the relationship of molecular gas and star formation, targeting both the validity and formulation of a star formation "law" ([58]) as well as the influence of galactic bars and gas inflow

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[1] SONG also imposed the criterion D$_{25}$ <70$'$ to exclude M33, which is the subject of the Engargiola et al. (2003) survey described in §3.2.

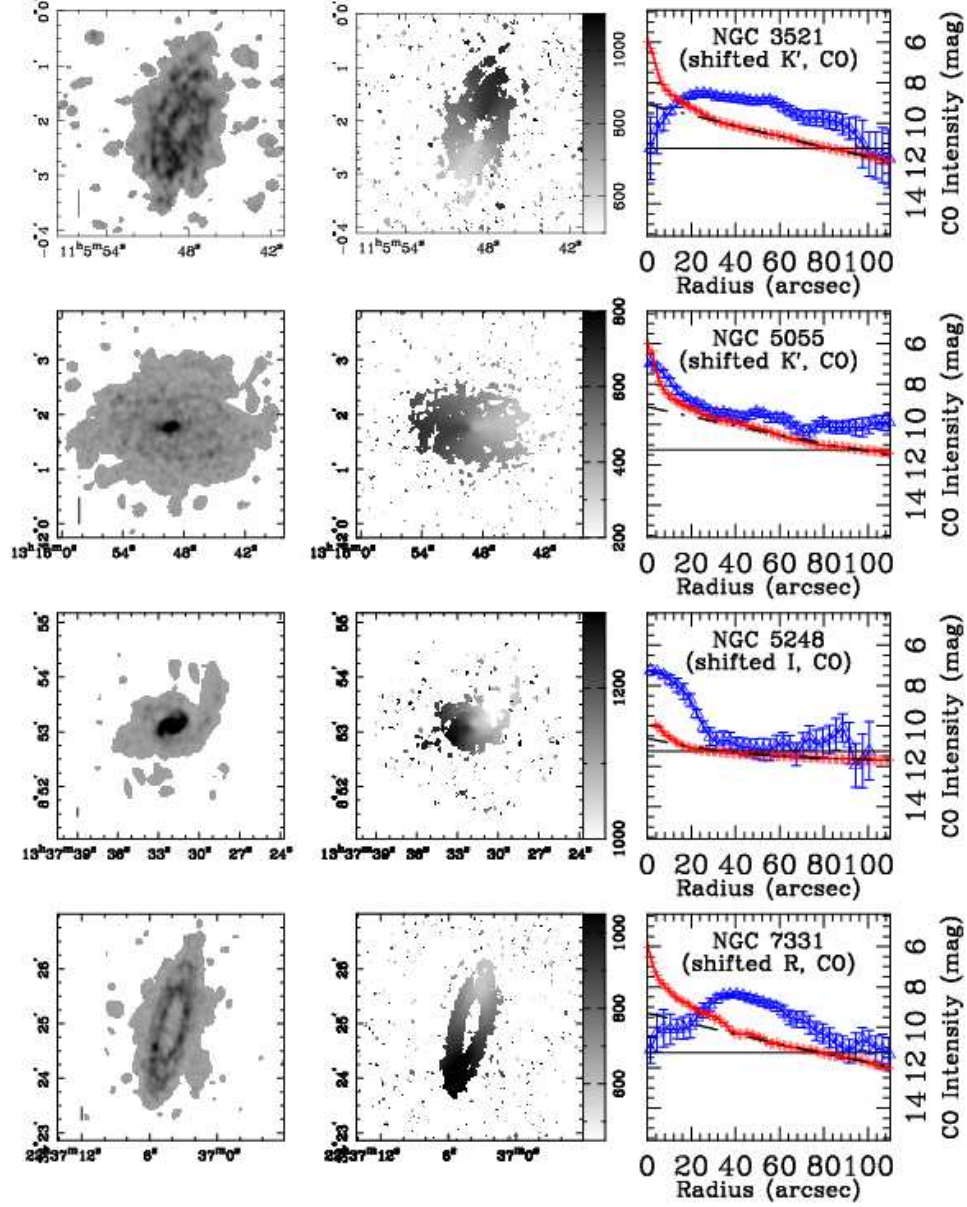[2] The BIMA SONG data are available at the following address: http://nedwww.ipac.caltech.edu/level5/March02/SONG/SONG.html

Fig. 1. BIMA SONG data for NGC3521, NGC5055, NGC 5248, and NGC7331 (top to bottom). **(left:)** integrated intensity (I_{CO}, with 1 kpc bar at lower left); **(center:)** velocity field (in km s^{-1}); and **(right:)** azimuthally averaged radial profiles for I_{CO} (triangles) and optical/NIR broadband light (crosses). For the purposes of comparison, I_{CO} has been converted to magnitudes for the radial profile (see [54]) and the optical/NIR profiles have been shifted vertically. An exponential fit to the outer part of each optical/NIR profile has been overplotted as a dot-dash line.

on the placement of star formation sites ([59]). In addition, the wealth of kinematic information available has enabled a systematic study of low-level streaming motions in a sub sample of $\sim$20 SONG galaxies [60].

Acknowledgements:

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