Combined Array for Research in Millimeter-wave Astronomy

Observing Proposal Cover Sheet

Proposal Number

c0104

General Proposal Information

Title	Date	TOO/Time Critical	Priority
The CARMA Survey Toward IR-bright Nearby Galaxies (CARMA STING)	2007-09-11	—	1

Scientific Category	Frequency Band	Level of Help Required
Extragalactic	3mm	None

Authors List

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Advisor must send a supporting letter if Thesis is checked. See Instructions.

Abstract

We propose the first semester of the CARMA Survey Toward IR-bright Nearby Galaxies (STING), which consists of ^{12}CO$(1 \rightarrow 0)$ observations of a set of 27 galaxies specifically designed to uniformly sample the “blue sequence” of actively star-forming galaxies. The target selection and observing strategy maximize the ability to study galactic disks across a cosmologically interesting span of stellar masses and specific star formation rates. We will survey out to $0.25\mathrm{R}_{25} - 0.5\mathrm{R}_{25}$ in all of our targets, in order to explore the transition between the molecular-dominated and the atomic-dominated regimes in galactic disks. Capitalizing on the unique capabilities and strengths of CARMA, we will obtain maps with high resolution (3”) and sensitivity ($15-22$ mJy in a 10 km s^{-1} channel, equivalent to $7-10$ M$_\odot$pc^{-2}). The STING galaxies have extensive optical (SDSS), far infrared (Spitzer, Herschel) and radio (VLA) ancillary data available. The main goal of the STING is to study the resolved relationship between star formation and gas content throughout disks, addressing the question of “what sets the rate of star formation in galaxies?”’. Spanning the blue sequence of star-forming galaxies will ensure that the conclusions of this study can be generalized to the full population of galaxies. This survey will provide a key data set to quantitatively explore the relation between gas reservoirs and star formation in galaxies, with the ultimate goal of understanding and characterizing the major processes that determine galaxy evolution. Complementing and building on the expertise of the BIMA SONG project, the CARMA STING will produce a data set of lasting archival value.

Source Information

#	Source	RA	DEC	Freq	B	C	D	# Fields	Species	Imag/SNR	Flex.HA
1	NGC1156	02:59	25:14	115.27	0	8	16	19	CO	Imaging	—
2	NGC1637	04:41	-02:51	115.27	0	8	16	19	CO	Imaging	—
3	NGC2681	08:53	51:18	115.27	0	8	16	19	CO	Imaging	—
4	NGC2782	09:14	40:06	115.27	0	8	16	19	CO	Imaging	—
5	NGC3147	10:16	73:24	115.27	0	8	16	19	CO	Imaging	—
6	NGC4151	12:10	39:24	115.27	0	8	16	19	CO	Imaging	—
7	NGC4214	12:15	36:19	115.27	0	16	0	19	CO	Imaging	—
8	NGC4254	12:18	14:24	115.27	0	8	16	19	CO	Imaging	—
9	NGC3486	11:00	28:58	115.27	0	8	16	19	CO	Imaging	—

Total Hours: 208.0

Special Requirements

None

Scientific Justification

We propose an extragalactic CO survey, the CARMA STING, which will target 27 galaxy disks from a sample designed to span a significant range of star-formation activities, stellar masses, specific star-formation rates (SSFR), and galaxy morphologies. The sample consists of FIR-bright galaxies with a wealth of existing ancillary data (Table 1), selected to fully span the SDSS blue sequence of active star-forming galaxies. The STING will take advantage of the strengths of CARMA — its unique combination of collecting area, field of view, and image fidelity — to deliver excellent images of galactic disks. Unlike previous interferometric surveys, the STING is designed to image these disks out to one-half of their optical radii (R_{25}), thus probing a new and critically important domain by beginning to sample the transition from molecule-dominated to the atomic-dominated galactic regions. This project will take 3 semesters to complete, and we request here time for its first semester.

The power of systematic surveys. Extragalactic CO surveys acutely lag behind optical surveys in their sampling of the universe. Most of the existing CO surveys used single-dish telescopes (e.g., Young et al. 1995 with FCRAO; Elfhag et al. 1996 with SEST; Böker et al. 2003 with IRAM; Kuno et al. 2007 with Nobeyama) with the consequent handicap in angular resolution. Only a handful of sizable CO surveys have used interferometers, chiefly: NUGA targeting 28 nearby AGN nuclei with PdBI (García-Burillo et al. 2003), BIMA SONG imaging of 44 nearby disks (Thornley et al. 1999; Helfer et al. 2003), OVRO MAIN, going after 15 nearby nuclei with different degrees of activity in two transitions (Baker et al. 2003), and the NMA/OVRO survey of the central arcminute of 20 CO-bright galaxies (Sakamoto et al. 1999).

The missing datum to put together a complete picture of galaxy evolution is the behavior of the gas reservoir. Recent observations suggest that decline in the co-moving quiescent SFR of star-forming galaxies since $z \sim 1$ (Noeske et al. 2006) may be caused by a progressive scarcity of gas to feed star formation (Noeske et al. 2006). The CARMA STING is designed to increase our understanding of the mechanisms by which atomic gas turns into molecular gas and ultimately into stars.

Sample design. Since the SDSS it has become clear that there is a very well-defined sequence relating stellar mass to star-formation activity, so that SFR is primarily dependent on stellar mass (Kauffmann et al. 2003, 2004). In the SFR vs. M_* plane galaxies separate into two well defined branches: the red branch of "dead" galaxies prevalent in high density environments, and the blue branch of "star-forming" galaxies, spanning a range of masses and star-formation activities (Fig. 1). Ours is the first CO survey specifically designed to sample the blue galactic sequence in the local universe.

Because obtaining the best science requires a number of ancillary data sets we have stressed in the selection criteria the availability of midIR and FIR photometry, HI data, and SDSS observations. The sample is composed of northern ($\delta > -20°$), moderately inclined ($i < 75$ deg) galaxies from the IRAS Revised Bright Galaxy Sample (RBGS) within 45 Mpc (Sanders et al. 2003). The galaxies were selected to uniformly sample 10 mass bins distributed between $M_* = 10^9$ and 3×10^{11} $M_\odot$. Within each bin the galaxies were ranked according to criteria designed to emphasize the availability of ancillary observations, lower inclinations, and the galaxy size match to the FOV of a 19-point mosaic. The 3 top galaxies per bin were selected where possible (some of the lower mass bins contained fewer than 3 galaxies), thus arriving at the sample size of 27 galaxies. Because of the heterogeneous nature of galaxies and their CO distributions (c.f., Regan et al. 2001), fewer than 10 mass bins and 3 galaxies per bin would result in too coarse a sampling of galaxy properties to yield general conclusions. The resulting sample very uniformly covers a range of stellar masses, star-formation activities, and morphological types (Fig. 1). We feel that, at this stage in the development of CARMA, selecting from the IRAS RBGS is important to maximize the impact of this study.

Differences and complementarities with other interferometric surveys. Unlike the NMA/ OVRO, NUGA and the MAIN surveys which are directed toward the study of the central region of galaxies the STING is geared toward the study of molecular disks, and it is thus most direclty comparable to BIMA SONG. The STING will have substantially better angular resolution (~ 3") than SONG ($\sim 6-7''$), better to much better sensitivity (depending on when the new 3 mm receivers are available on the 10m dishes), considerably better image fidelity and calibration owing to CARMA's 105 baselines, and far superior galaxy coverage ($\sim 30\%$ of the optical disk compared to $\sim 6\%$ in SONG; Fig. 1c). With the STING we will sample farther into galaxy disks and cover regions where atomic gas is dominant. These are the key data necessary to discriminate among star-formation recipes. In order to enlarge the overall sample of galaxies with interferometric CO images, *we have purposefully avoided overlap with SONG*. Figures 1 graphically describes the sample and compare it to SONG.

Science with the STING. A major goal of the CARMA STING is to help link star formation and the ISM to our understanding of galaxy evolution by asking "What sets the rate of star formation in galaxies?". We will use the STING observations to carry out quantitative tests of a suite of theories about where and under which conditions GMCs and stars form. The resolution of CARMA will allow us to work at sub-kpc scales on a pixel-by-pixel basis (Fig. 1b) . The ancillary data (HI, optical, IR, and UV) will let us construct maps of the star formation rate and the stellar and total gas mass to accompany the CO maps. With rotation curves derived from the CO and HI, and molecular gas surface densities from FIR and CO, we can model the predicted SFR and compare it to observations. In a nutshell, the proposed observations will allow us to:

- Perform resolved studies of the relation between SFR and gas content in galactic disks, addressing the relations between SF activity and molecular and atomic gas, and studying the SF efficiency (SFE) in a variety of environments. • Quantitatively study the distribution of the molecular gas in relation to the stellar and atomic components. • Perform accurate mass modeling of galaxies, as the STING will yield a wealth of accurate kinematic data to study the transport of gas in galaxy disks. • Clarify how the FIR/radio correlation differs between "normal" and "starburst" galaxies, by comparing the local correlation with measurements of gas surface density which should correlate tightly with the magnetic field strength. • Study the heating and cooling equilibrium of gas in disks, by combining the STING data with spectroscopic FIR observations by Spitzer and Herschel, and planned CO surveys of the 2-1 and 3-2 transitions by the JCMT. • Model the FIR dust continuum in relation to the molecular gas distribution, in combination with existing Spitzer data and future Herschel and SCUBA2/LABOCA imaging.

What sets the rate of star formation in galaxies? In the last decade, theories consistent with existing data have argued that star formation is regulated by: Coriolis forces and instabilities in gas disks (Kennicutt 1998; Martin & Kennicutt 2001); galactic shear (Hunter et al. 1998); cloud-cloud collisions (Tan 2000); the formation of a cold phase above a certain column threshold (Schaye 2004); the ability of stars to bring gas to high densities at the midplane (Wong & Blitz 2002; Blitz & Rosolowsky 2006); or large scale instabilities in the gas disk driven by stars (Li et al. 2005, 2006; Yang et al. 2007). This striking variety of answers emphasizes the need for a data set designed to test these theories.

The CARMA STING will provide a key data set to quantitative explore the relation between the gas reservoirs and the star formation in galaxies, with the ultimate goal of understanding and characterizing the major processes that determine galaxy evolution. This survey takes advantage of the unique capabilities of CARMA.

• Baker, A. J., et al. 2003, Active Galactic Nuclei: From Central Engine to Host Galaxy, ASPCS 290, 479 • Blitz, L., & Rosolowsky, E. 2004, ApJ, 612, L29 • Blitz, L., & Rosolowsky, E. 2006, ApJ, 650, 933 • Böker, T., Lisenfeld, U., & Schinnerer, E. 2003, A&A, 406, 87 • Boselli, A., et al. 2001, AJ, 121, 753 • Elfhag, T., et al. 1996, A&AS, 115, 439 • García-Burillo, S., et al. 2003, A&A, 407, 485 • Helfer, T. T., et al. 2003, ApJS, 145, 259 • Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, ApJS, 112, 315 • Hunter, D. A., Elmegreen, B. G., & Baker, A. L. 1998, ApJ, 493, 595 • Kauffmann, G., et al. 2003, MNRAS, 341, 54 • Kauffmann, G., et al. 2004, MNRAS, 353, 713 • Kennicutt, R. C., Jr. 1998, ApJ, 498, 541 • Kuno, N., et al. 2007, PASJ, 59, 117 • Li, Y., Mac Low, M.-M., & Klessen, R. S. 2005, ApJ, 620, L19 • Li, Y., Mac Low, M.-M., & Klessen, R. S. 2006, ApJ, 639, 879 • Martin, C. L., & Kennicutt, R. C., Jr. 2001, ApJ, 555, 301 • Noeske, K. G., et al. 2006, ApJl, 640, L143 • Sakamoto, K., et al. 1999, ApJS, 124, 403 • Salim, S., et al. 2007, ArXiv:0704.3611 • Schaye, J. 2004, ApJ, 609, 667 • Tan, J. C. 2000, ApJ, 536, 173 • Thornley, M., et al. 1999, Ap&SS, 269, 391 • Wong, T., & Blitz, L. 2002, ApJ, 569, 157 • Young, J. S., et al. 1995, ApJS, 98, 219

Table 1

Name	Morph	RA (h)	Dec (deg)	Dist (Mpc)	Incl (deg)	D_{25} (")	M_* ($M_\odot$)	SFR ($M_\odot$ yr^{-1})	SI	Sp	He	VLA	Class
NGC 0337	SBcd	1.00	-7.6	21.6	50.6	175	10.0	0.3	N	YY	P	DC	
NGC 0772	Sb	1.99	19.0	28.7	48.5	274	11.1	0.6	N	Y		DC	H:T2
NGC 1156	IB	3.00	25.2	7.0	43.1	173	8.9	-0.9	N	Y		DCB	H
NGC 1569	IB	4.51	64.9	4.6	64.7	238	9.2	-0.4	N	Y	G	DCB	H
NGC 1637	Sc	4.69	-2.9	10.2	31.1	191	9.8	-0.5	N	Y		DC	
NGC 2681	S0-a	8.89	51.3	12.5	15.9	235	10.2	-0.4	Y	Y		B	L1.9
NGC 2782	SABa	9.23	40.1	39.5	45.1	195	10.7	0.7	Y	Y		DCB	H
NGC 3147	Sbc	10.28	73.4	41.4	29.5	243	11.3	1.0	N	Y		DC	S2
NGC 3198	Sc	10.33	45.5	13.8	70.0	388	10.2	-0.1	Y	YY	P	DCB	H
NGC 3486	Sc	11.01	29.0	9.2	46.0	349	9.7	-0.5	Y	Y		DB	S2
NGC 3593	S0-a	11.24	12.8	5.0	74.6	281	9.5	-0.7	Y	Y		DCB	H
NGC 3949	Sbc	11.90	47.9	13.6	56.5	136	9.8	-0.0	Y	Y		B	H
NGC 4151	SABa	12.18	39.4	19.0	21.0	173	10.6	-0.1	Y	Y	G	CB	S1.5
NGC 4214	I	12.26	36.3	3.7	43.7	408	9.0	-1.0	Y	Y	G	DCB	H
NGC 4254	Sc	12.31	14.4	15.3	32.0	302	10.6	0.7	Y	YY	G	DCB	H
NGC 4273	Sc	12.33	5.3	15.3	48.5	131	9.7	0.0	Y	Y		CB	H
NGC 4501	Sb	12.53	14.4	15.3	61.0	519	10.9	0.5	Y	Y	G	C	S2
NGC 4536	SABb	12.57	2.2	14.9	58.9	425	10.4	0.4	Y	YY	G	DCB	H
NGC 4568	Sbc	12.61	11.2	15.3	66.0	258	10.4	0.4	Y	Y	G	DCB	H
NGC 4605	SBc	12.67	61.6	3.9	70.4	354	9.1	-1.0	Y	Y		DCB	
NGC 4654	SABcd	12.73	2.2	15.1	56	283	10.3	0.2	Y	Y		DC	H
NGC 4808	Sc	12.93	4.3	19.7	69.2	142	10.0	0.1	Y	Y	G	DCB	
NGC 5371	Sbc	13.93	40.5	41.1	54.0	239	11.2	0.8	Y	Y		DB	L2
NGC 5713	SABb	14.67	-0.3	26.7	48.2	148	10.5	0.8	Y	YY	P	DCB	
NGC 5728	Sa	14.71	-17.3	38.3	59.0	192	10.9	0.7	N	Y		C	
NGC 6503	Sc	17.82	70.1	3.8	73.7	371	9.2	-1.1	N	Y		DCB	T2/S2
NGC 6951	SABb	20.62	66.1	24.0	52.5	193	10.9	0.7	N	Y		DCB	S2

Table of the sample detailing galaxy name, morphology, J2000 coordinates, inclination, major axis extent (D_{25}), log of the stellar mass based on K-band magnitude (M_*), log of the star formation rate based on FIR luminosity (SFR), existing SDSS photometry (Sl), existing Spitzer IRAC *and* MIPS photometry (Sp; YY indicates is part of the SINGS project with a wealth of other ancillary observations), Herschel observations (He, G denotes guarantee time observation, P denotes in PHOENIGS proposal), configurations for archival VLA HI observations, and Ho et al. (1997) nuclear classification (Class; H denotes HII galaxy, T for Transition type, L for Liner, S for Seyfert).

Technical Justification

We will eventually survey 27 galaxies with spatial resolution of $50 - 600$ pc, covering out to $0.5\mathrm{R}_{25}$ in 19-point mosaics, attaining a 3σ point mass sensitivity $\sim 1.5 \times 10^6\ d^2_{15\ \mathrm{Mpc}}$ $\mathrm{M}_\odot$ in a 10 km s^{-1} channel. observations will be necessary. Two galaxies (NGC 4214 and NGC 4605) have extensive low resolution observations by BIMA and/or OVRO. For each of these we request only two high resolution (C-array) tracks. The remaining galaxies in our sample will be observed with optimally matched mosaic patterns in three tracks over two configurations (D-D-C). To complete this project will require a total of 608 hours of array time, which we will pace over 3 semesters. The first semester targets consists of those galaxies with the lowest inclinations in the sample, given the limitations of the present correlator. Two years after the completion of the observations we expect to release the data in archival form.

• **Resolution.** Our science goals require ~ 500 pc resolution. A combination of one C array track and two D array tracks will yield a ~ 3" (FWHM) robustly synthesized beam, or 200 pc spatial resolution at the median distance of our sample. • **Coverage.** Mosaicing to half of the optical radius, R_{25}, allows us to probe out to the atomic-dominated regime (the transition from H_2- to HI-dominated usually occurs between ~ 0.25 and $0.5\mathrm{R}_{25}$). The average optical size of a galaxy in our sample is $d_{25} = 240''$. Our default observing mode will be a 19-point mosaic with a width of full sensitivity of ≈ 120". • **Sensitivity.** We aim for a uniform sensitivity of ≈ 22 mJy beam^{-1} (0.22 K) in a 10 km s^{-1} channel and a $3''$ synthesized beam within the 117" mosaic. By contrast, the interferometric part of the SONG survey achieved typical sensitivities $50 - 60$ mJy beam^{-1} rms (Helfer et al. 2003; Table 2), with beam areas ~ 4 times as large. The STING sensitivity will be substantially better than that of SONG. • **Spectral configuration.** We will configure the correlator to observe in 3 partially overlapping 62-MHz windows with 2.5 km s^{-1} resolution. This will provide a total velocity width of 400 km s^{-1}, sufficient to span the CO emission from our targets after accounting for overlap between the bands. • **Zero-spacing single-dish observations.** We intend to obtain single-dish (SD) zero-spacing data for this project. This proposal includes co-Is from institutes linked to two major SD telescopes, well placed to lead the effort to obtain observations.

The following tasks will be pursued by the team of co-Is: Wong, with help from Bolatto, Vogel, Leroy, and Rosolowsky will lead the effort of producing mm-wave cubes from the CARMA observations. Wong and Vogel will also devote a substantial effort to further analysis of the SONG data and improvement of its data products. Bolatto and Wong will set up a website for the distribution of the STING data. Calzetti will lead the effort of producing Spitzer/Herschel images and spectra. Calzetti will also head the single-dish LMT observations. Rosolowsky, who is joining the UBC faculty and will have internal access to the JCMT, will pursue JCMT observations and combine them with CARMA, both for heterodyne and SCUBA2. Walter and Leroy will lead the effort of pursuing IRAM 30m/APEX observations. Ott, with help from Blitz, Walter, and Wong will be in charge of producing the necessary VLA radio continuum and HI cubes from archival data. West will lead the SDSS and GALEX photometry effort. Ancillary optical observations, when necessary, will be pursued by Walter, Vogel, Blitz, and Bolatto using their special institutional access to Calar Alto, KPNO, and Keck/Lick. Blitz will pursue ancillary HI observations of the extended galaxy envelopes with the ATA. For a list of the people that agree to take the lead on the different science studies that will take place using the STING and ancillary data sets, see `http://www.astro.umd.edu/~bolatto/STING`.

Institutional time charges and scheduling. The entire STING project requires approximately 200 hours per semester during 3 semesters, for a total of 608 hours. *We request here time to complete semester 1 of the project.* If that is granted, we will resubmit for semesters 2 and 3. The authors wish to break up the hour charge per institution in the following manner:

• Bolatto, Vogel (UMD): 17.5% of the time • Wong (UIUC): 17.5% of the time • Blitz, West (UCB): 20% of the time • Ott (CIT): 15% of the time • Calzetti, Kennicutt, Walter, Rosolowsky, Leroy (external): 30% of the time

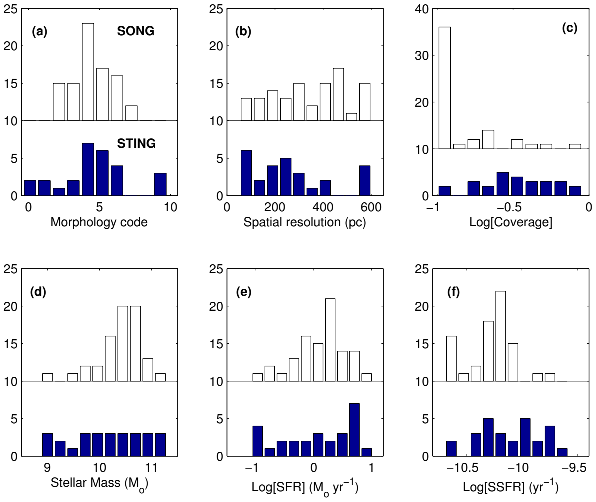

Fig. 1.— Histograms contrasting the distribution of several parameters for the STING and SONG samples. The panels indicate the distributions of: a) morphological types from LEDA. b) Spatial resolution on source. c) Log of the fraction of the source area (measured by D_{25}) covered. d) Stellar mass, M_*, as measured by K-band light. e) Log of SFR. f) Log of specific SFR, or the inverse time to form M_* at current SFR. The CARMA STING is designed to uniformly sample the stellar mass range of 10^9 to 3×10^{11} $\mathrm{M}_\odot$, probing a wider range of SFRs, SSFRs, FIR luminosities, and morphologies than SONG. The STING is also designed to cover a larger fraction of galaxy disks than SONG (median of 30% versus 6%), with no loss of spatial resolution and a factor of two better sensitivity (~ 22 vs. $50 - 60$ mJy beam^{-1}.