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First Results from CARMA: The Combined Array for Research in Millimeter-wave Astronomy

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ABSTRACT

The Combined Array for Research in Millimeter-wave Astronomy (CARMA) comprises the millimeter-wave antennas of the Owens Valley Radio Observatory (OVRO), the Berkeley-Illinois-Maryland Association (BIMA) Array, and the new Sunyaev-Zel'dovich Array (SZA). CARMA consists of six 10.4-m, nine 6.1-m, and eventually eight 3.5-m diameter antennas on a site at elevation 2200 m in the Inyo Mountains near Bishop, California. The array will be operated by an association that includes the California Institute of Technology and the Universities of California (Berkeley), Chicago, Illinois (Urbana-Champaign), and Maryland. Observations will be supported at wavelengths of 1 cm, 3 mm, and 1.3 mm, on baselines from 5 m to 2 km. The initial correlator will use field programmable gate array (FPGA) technology to provide all single-polarization cross-correlations on two subarrays of 8 and 15 antennas with a total bandwidth of 8 GHz on the sky. The next generation correlator will correlate the full 23-antenna array in both polarizations. CARMA will support student training, technology development, and front-line astronomical research in a wide range of fields including cosmology, galaxy formation and evolution, star and planet formation, stellar evolution, chemistry of the interstellar medium, and within the Solar System, comets, planets, and the Sun. Commissioning of CARMA began in August 2005, after relocation of the antennas to the new site. The first science observations commenced in April 2006.

Keywords: Radio astronomy, millimeter-wave astronomy, millimeter-wave telescopes, millimeter-wave instrumentation

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1. INTRODUCTION

The Combined Array for Research in Millimeter-wave Astronomy (CARMA) has been constructed from nine of the 6.1-m antennas of the Berkeley-Illinois-Maryland Association (BIMA) array (Welch et al. 1996, Fig. 1) and the six 10.4-m antennas of Caltech's Owens Valley Radio Observatory (OVRO) millimeter array (Padin et al. 1991, Fig. 2). The new array will be operated by an association that includes the California Institute of Technology and the Universities of California (Berkeley), Chicago, Illinois (Urbana-Champaign), and Maryland. The antennas were relocated to the new CARMA site at Cedar Flat in the Inyo Mountains of eastern California. The University of Chicago has recently constructed the Sunyaev-Zel'dovich Array (SZA) of eight 3.5-m antennas at OVRO (Fig. 3). In 2008 these antennas will be moved to Cedar Flat to join CARMA.

The idea of merging the OVRO and BIMA arrays to form a new instrument at a superior site has been discussed for at least a decade. The combined instrument will have imaging capabilities superior to either the BIMA or OVRO arrays. At the higher-elevation site, the effects of the atmosphere will be substantially reduced. Observations at 1 mm will be routine, and there will be no need to limit millimeter observations in summer. In May 2003, the CARMA partners formally agreed to merge their separate arrays to construct CARMA, and within a year the final site was selected and construction could begin. As well as providing the community with a premier millimeter imaging instrument, CARMA will enable the education of the next generation of millimeter astronomers through hands-on observational and technical training of students and post-doctoral scholars.

2. CARMA CHARACTERISTICS

2.1 Antennas and Receivers

The CARMA antennas remain essentially unmodified from their days in the BIMA and OVRO arrays, with the exception of a new base that has been provided for the BIMA antennas. This base allows the use of a single antenna transporter for all antennas, and should improve antenna thermal performance.

CARMA will initially observe with SIS receivers in the 3-mm (70–116 GHz) and 1-mm (215–270 GHz) bands with a 4 GHz IF bandwidth. Below 84 GHz, only the BIMA antennas will be available, while at 3-mm only the OVRO antennas will provide the full 4 GHz IF. Observing in the 1-cm band will be possible when the SZA joins CARMA. The expected sensitivity of the array is shown in Table 1.

Table 1. Sensitivity

Water Vapor Percentile	Continuum (mJy/√min)		Line (K/√min)	
	σ 100 GHz	σ 250 GHz	σ 100 GHz	σ 250 GHz
		a) CARMA in 2006		
10%	4.6	5.8	63.5	9.9
25%	4.9	7.7	67.6	13.2
50%	5.1	9.1	69.0	15.6
		b) CARMA in 2008		
10%	0.61	2.0	7.4	3.0
25%	0.67	3.0	8.2	4.5
50%	0.70	3.7	8.5	5.6

Note. Line sensitivities assume a θ=1″ beam and Δv=1 km s^{-1}. CARMA upgrades anticipated for 2008 include new low noise receivers, dual-polarization at 1 mm, 4 GHz IF for the 6-m antennas at 3 mm, and improved aperture efficiency for the 10.4-m antennas. The 10, 25, and 50% water vapor percentiles for Cedar Flat correspond to 2, 3.7, and 4.8 mm of water vapor. Sensitivity calculations do not include losses from atmospheric decoherence.

2.2 Site and Array Configuration

The new CARMA site is at elevation 2200 m, just 20 minutes drive from OVRO. Year-round operations are facilitated by the proximity of California highway 168, which runs through the site and is cleared of snow year-round. The Sierra Nevada range is just east of the site and provides an excellent rain shadow, resulting in a "high desert" climate with superior observing conditions. Pre-construction site testing revealed that the 225 GHz 50th percentile opacity is 0.2–0.25, about half the value for the BIMA or OVRO sites.

CARMA will have a unique spatial dynamic range. Observations in five reconfigurable arrays with baselines from 5 m to 2 km (Fig. 4) will provide resolution and wide field imaging unprecedented in the millimeter band (Table 2). This heterogeneous array of antennas will afford excellent imaging by allowing a larger range of spatial frequencies to be sampled instantaneously, and by using the varying primary beam patterns to decouple the source brightness distribution from the primary beam illumination. Total power data can be provided by the 10.4-m antennas, which are significantly larger than the shortest interferometer spacings.

Table 2. FWHM Beam Sizes (arcsec) for a 4-hr track at 230 GHz

Declination	A	B	C	D	E
30	0.15 × 0.12	0.37 × 0.30	0.90 × 0.75	2.2 × 1.9	4.5 × 3.9
0	0.15 × 0.15	0.38 × 0.37	0.94 × 0.90	2.4 × 2.2	5.0 × 4.4
−30	0.32 × 0.15	0.75 × 0.38	1.88 × 0.92	4.7 × 2.3	7.6 × 3.5

2.3 Correlator

The flexible first light correlator will use field programmable gate array (FPGA) technology to provide all single-polarization cross-correlations on two subarrays of 8 and 15 antennas with a total IF bandwidth of 4 GHz (8 GHz on the sky). Polarimetry will be possible in a time-sharing mode. The correlator is based on the COBRA system developed for the OVRO millimeter array. To provide the first 1.5 GHz, the 4 GHz 6-antenna COBRA correlator has been "recycled" into a 1.5-GHz 15-antenna correlator. This is being supplemented with additional hardware using more capable digitizers and larger FPGAs to provide the full 4 GHz bandwidth. The spectral modes available are shown in Table 3. The eight 500-MHz bands will be independently tunable.

Table 3. Expected spectral modes of the new CARMA correlator in each 500-MHz band.

Bandwidth (MHz)	Channels (per sideband)	δV (3 mm) (km s^{-1})	V_{tot} (3 mm) (km s^{-1})	δV (1 mm) (km s^{-1})	V_{tot} (1 mm) (km s^{-1})
500	100	15	1500	5	500
250	175	4.3	750	1.4	250
125	250	1.5	375	0.5	125
62	300	0.63	188	0.21	62.5
31	350	0.27	93.8	0.09	31.2
8	400	0.06	23.4	0.02	7.81
2	400	0.015	5.86	0.005	1.95

2.4 Monitor and control

The monitor and control system is implemented as a distributed system, using the Linux OS running on Intel hardware. Communication between the distributed nodes is done with CORBA over ethernet (100 & 1000 mbps). Embedded processing is implemented on microprocessors connected to Linux hosts over Canbus. The high level software is written in C++, the embedded code in C, the user interface code in Java, and the observer control layer is done in python. The observer python control scripts have been effective in providing both low level and high level control capability. The average data rate for CARMA is about 14 GB/day with a peak that is ten times the average.

The system is designed with sufficient compute power and queueing to eliminate the need for an RTOS. Hardware and software failures are inevitable and will be tolerated by the system and occur gracefully. There is an emphasis on monitoring, using monitor data for internal synchronization, astronomical data headers, fault detection, and engineering hardware diagnosis. The philosophy is to monitor everything possible. There are more than 60,000 monitor points in the system, each sampled at 2 Hz or faster, with all the data recorded in a database. The fast sampled data are recycled on the timescale of about a month, allowing problems requiring high time resolution to be addressed. The permanent archive has the average, minimum and maximum values for all monitor points on both a one minute timescale and for the requested astronomical integration.

2.5 Database and Archive

The CARMA archive will build on the existing BIMA and OVRO archive systems and provide remote access and retrieval services for the CARMA astronomical, scientific, and engineering communities. It will be located at the UIUC National Center for Supercomputing Applications (NCSA) facility. Initially, basic archive search and retrieval options will be available. More complete web-based search and retrieval capabilities for the archive are now being developed so that the user community can locate and retrieve the data required to meet the full scientific goals of each observing project. Archive operations and curation processes that will ensure data integrity and the uninterrupted flow of data from the telescope are also being put in place.

The pipelined CARMA data reduction capability, based on the existing BIMA pipeline, is aimed at expanding the CARMA user community and increasing the science yield of the telescope. To ensure complete success, a number of important problems for fully-automated pipeline reduction of data from mm-wavelength interferometers will have to be addressed. These include the scientific optimization of pipeline reduction, fidelity assessment of automated images, and automated flagging of bad data.

3. SCIENTIFIC MOTIVATION

CARMA will possess a unique combination of subarcsecond resolution and wide bandwidth. A broad range of scientific investigations will benefit from the large performance gains due to the merger of the arrays, relocation of the antennas to a higher site, and technical developments over the coming years. CARMA will be used to:

- Test models of galaxy cluster properties and evolution from detailed imaging of the integrated pressure profiles (SZ Effect).
- Trace the evolution of molecular gas from primordial galaxies to the present epoch.
- Resolve the (sub)mm extragalactic background emission into its faint galaxy population, revealing the star formation history of the early universe hidden from optical view.
- Test galaxy evolution models by complementing the COSMOS, DEEP, and GOODS surveys with dynamical masses and molecular gas fractions.
- Survey molecules that trace dense gas in starburst nuclei and mergers at sub-arcsecond resolution to understand their enhanced star formation and the origin of supermassive star clusters.
- Map magnetic fields at high angular resolution to determine their role in molecular cloud evolution and star formation.
- Determine the mass distribution of condensations of dust in a range of cloud cores and test theories of clustered star formation.
- Image energetic protostellar outflows over a range of spatial scales, including the highest resolution, to elucidate the processes at work close to the star, and the effects on the ISM at greater distances.
- Constrain planetary system formation scenarios through surveys of the primordial gas+dust evolution in young star clusters and determinations of the radial, vertical and chemical structure within disk analogs of the early solar nebula.

- Search for resonant structures produced by orbiting planets in debris disks detected with Spitzer.
- Characterize at high angular resolution the variable composition and dynamics of planetary, satellite, and cometary atmospheres.

4. CONSTRUCTION, COMMISSIONING AND FIRST LIGHT

The development of CARMA began in 2001 with the design of common electronics modules and signal distribution systems, and planning for new computing systems. Over the last few years, attention has shifted to site construction, relocation of the antennas, installation of the upgraded electronics, and implementation of the new software. Major milestones include:

- Construction of the access road & leveling of the central array area (Aug 04)
- Installation of the microwave relay tower (Aug 04)
- Relocation of nine BIMA antennas (Sep 04; Fig. 5)
- Completion of first 25 antenna pads (Nov 04)
- Relocation of six OVRO antennas with upgraded electronics and cryogenics (Mar 05 & Jun 05; Fig 6.)
- Construction of site buildings and power plant (May 05)
- Installation of power and fiber to the first 25 pads (May 05)
- Reassembly of BIMA antennas (Jun 05–Aug 05; Fig. 7)
- Start of optical pointing observations on OVRO antennas (Jun 05)
- Acquisition of first fringes on test tone (Aug 05)
- Astronomical fringes with fringe tracking (Sep 05)
- First “image” of a calibrator source (Nov 05)
- Installation of 1.5 GHz of downconverter and correlator (Jan 06)
- Completion of pads for the C, D, and E, configurations (Dec 06) (baselines to 350 m N-S and 250 m E-W)
- First mosaic (Apr 06; Figure 8).

The final milestone indicates the readiness of the system for shared-risk science observations, which have already begun in parallel with continuing commissioning and system characterization tasks. This summer, the first proposals will be solicited for observations in the winter 2006-2007 observing period. Thirty percent of the observing time will be made available to outside observers.

5. FUTURE DEVELOPMENTS

Over the next three years, CARMA will enhance sensitivity with new 1-mm and 3-mm receivers. The dual-polarization 1-mm receivers will use SIS technology and a novel waveguide orthomode transducer developed by CARMA. They will have receiver temperatures approaching 30 K, bandwidth > 4 GHz, and a tuning range of 210–270 GHz. At 3-mm, low-noise monolithic microwave integrated circuit (MMIC) receivers with a bandwidth ≥ 8 GHz will allow observations with a total system temperature of ~85 K. Over the next two years a correlator capable of handling all 23 antennas with 8 GHz × 2 polarizations will be developed. This correlator will be constructed starting in 2008.

Also in 2008, the Sunyaev-Zel'dovich Array will join CARMA at Cedar Flat, adding eight 3.5-m antennas to the 6.1-m and 10.4-m antennas. During construction of the 23-antenna correlator, the current CARMA correlator will allow observations that make use of any two of three antenna types, while the SZA correlator will make simultaneous observations possible with the remaining antennas.

Over the next decade, CARMA's antennas and modest complexity will allow the incorporation of focal plane arrays for millimeter-wave imaging of wide fields with high spatial resolution and image fidelity. It is expected that advances in

MMIC technology will allow the installation of 48 receivers at the focal plane. With a bandwidth of 8 GHz, CARMA will be able to mosaic the sky with a speed approximately twice that of the Atacama Large Millimeter Array (ALMA).

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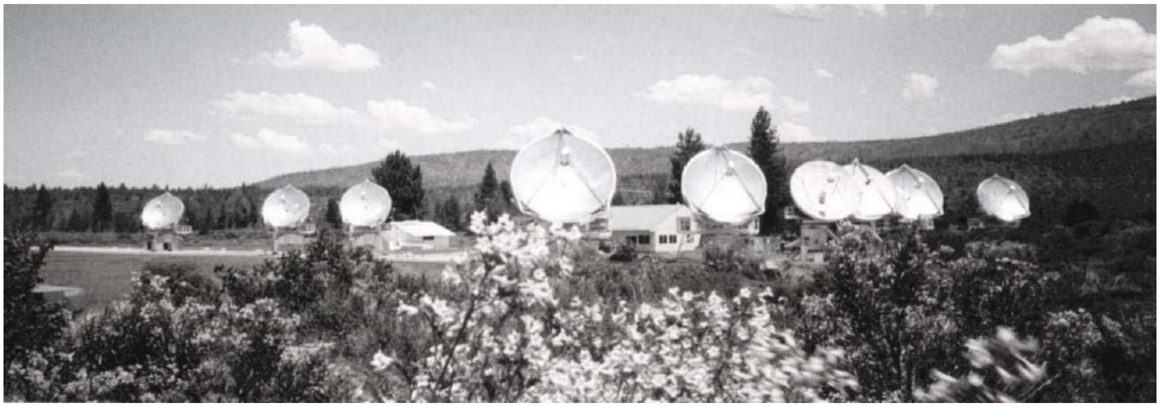

Fig. 1. The Berkeley-Illinois-Maryland Association array at Hat Creek

Fig. 2. The Owens Valley Radio Observatory millimeter array

Fig. 3. The Sunyaev-Zel'dovich Array at the Owens Valley Radio Observatory is expected to join CARMA in 2008

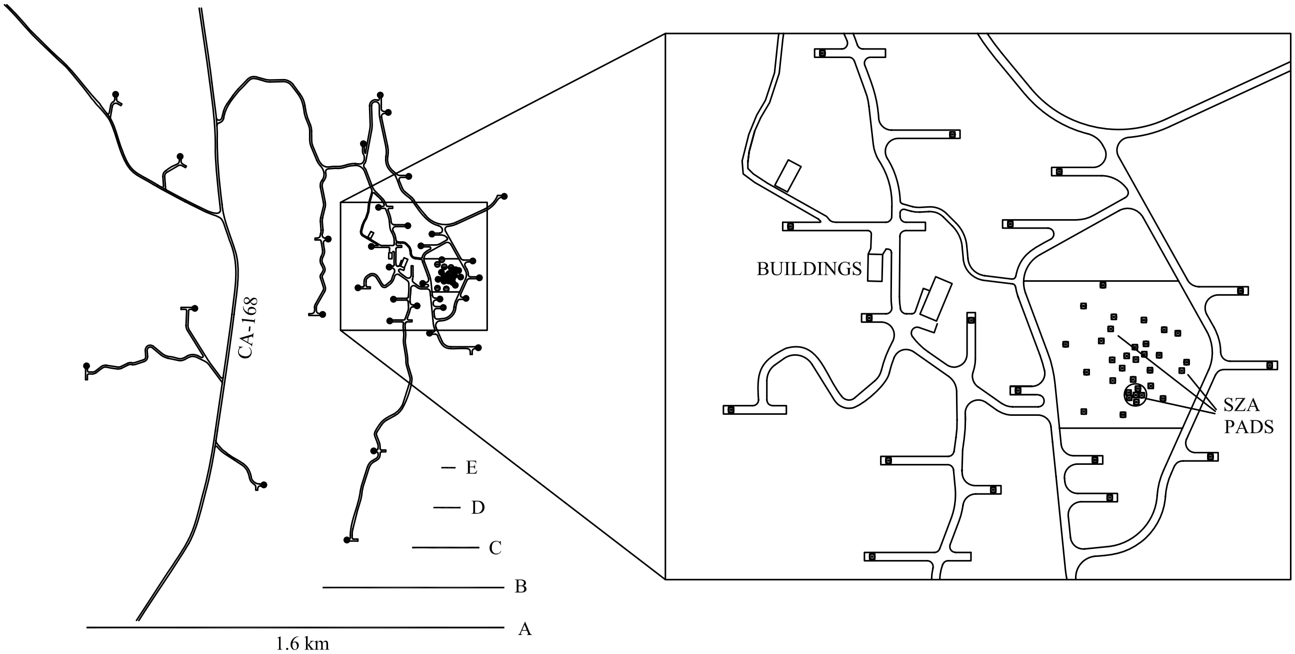

Fig. 4. Distribution of the CARMA antenna pads, showing the extent of the antenna configurations

Fig. 5. The first BIMA antenna leaves Hat Creek for its 512-mile journey south to Cedar Flat

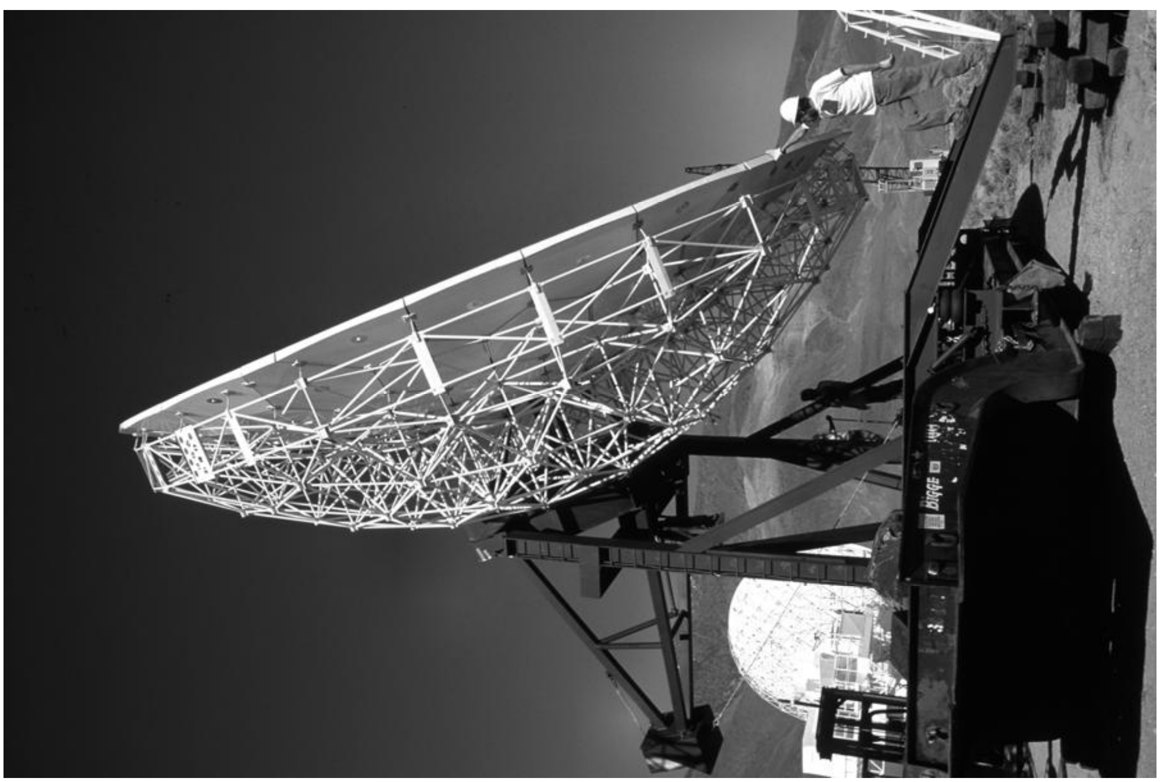

Fig. 6. Each OVRO reflector was mounted on a tilting fixture to enable it to pass through the “Narrows” on California highway 168

Fig. 7. CARMA antennas at Cedar Flat, Inyo Mountains, California

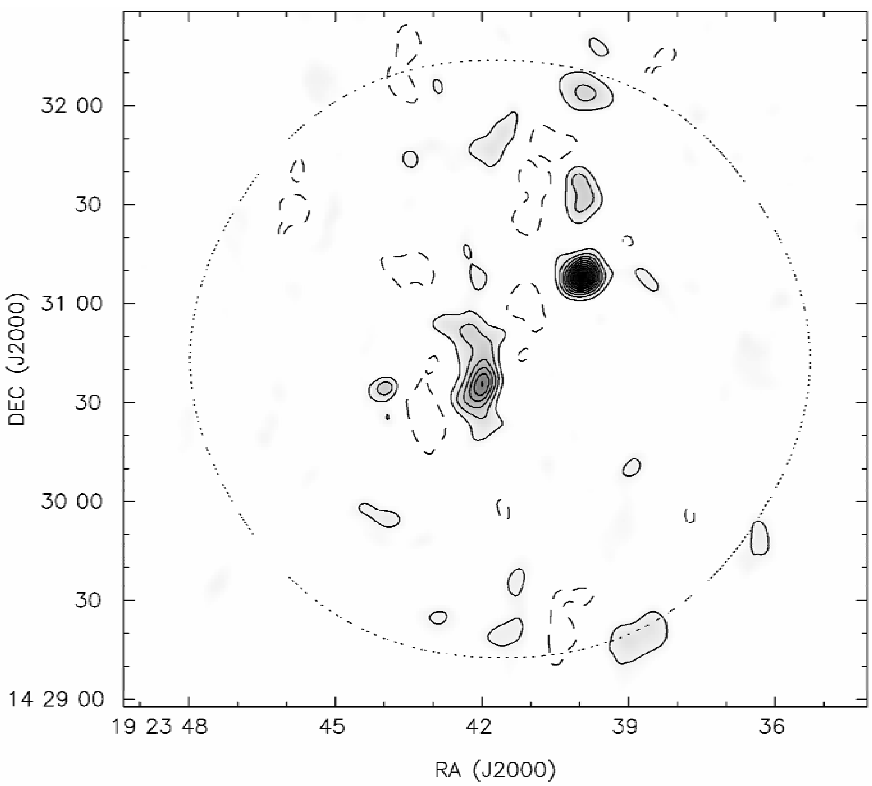

Fig. 8. An 88.5-GHz continuum mosaic of W51 made with the hybrid array of 10 m and 6 m antennas that covers the whole BIMA primary beam (shown by the circle)