CLASS: Cosmic Lens All-Sky Survey

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Abstract

The Cosmic Lens All-Sky Survey (CLASS), is an international (USA, UK and Netherlands) collaborative program aimed at obtaining high-resolution radio images of over 10000 flat-spectrum radio sources in order to create the largest and best studied statistical sample of radio-loud gravitationally lensed systems. With this survey, combined with detailed studies of the lenses found therein, powerful constraints can be placed on the cosmography (ie. expansion rate, mean density, and cosmological constant) of the Universe. CLASS is aimed at identifying lenses where multiple images are formed from compact flat-spectrum radio sources, which should be easily identifiable in the radio maps. In three observing "seasons" in 1994, 1995, and 1998, CLASS has observed over 12,000 radio sources. When combined with the JVAS survey, the CLASS sample contains over 15,000 images and at least 17 lenses, with 11 in CLASS so far as well as a number of candidates still being followed up. In this poster, we present a summary of the CLASS observations, the JVAS-CLASS sample, and statistics on subsamples of the survey.

Overview

The Cosmic Lens All-Sky Survey (CLASS) is an international (USA, UK and Netherlands) collaborative project to map more than 10,000 radio sources in order to create the largest and best studied statistical sample of radio-loud gravitationally lensed systems. With this survey, combined with detailed studies of the lenses found therein, powerful constraints can be placed on the cosmography (ie. expansion rate, mean density, and cosmological constant) of the Universe. CLASS is aimed at identifying lenses where multiple images are formed from compact flat-spectrum radio sources. The lens configurations should be easily identifiable in the radio maps. Thus, CLASS is most efficient at finding galaxy-mass lenses (which will dominate the counts for surveys not targeted at clusters) with separations of around a few arcseconds. CLASS will also be able to detect more extreme lensed systems with larger separations, which are due to clusters of galaxies. Of course, the CLASS database will also contain a rich sample of radio galaxies and quasars for the study of AGN phenomena.

The Very Large Array(VLA) is being used as the primary instrument for the CLASS survey. In its largest "A" configuration, the VLA provides high-quality images with an angular resolution of 0.2 arcseconds at a typical observing frequency of 8.5 GHz. In the first three primary phases of CLASS carried out from 1994 – 1998, a total of 12831 target radio sources were mapped, of which nearly 85% were detected. If we include the approximately 2400 JVAS sources, then we have a total of over 15000 sources already observed.

JVAS-CLASS Observing Sessions

Session	Dates	N_{obs}	Refs
JVAS	Feb 1990 – Dec 1992	2400	[17],[2],[23]
CLASS-1	Feb 1994 – May 1994	3247	[15]
CLASS-2	Aug 1995 – Sep 1995	4462	[4]
CLASS-3	Feb 1998 – May 1998	5096	[16]
Total	—	15205	
Statistical Sample	—	11685	

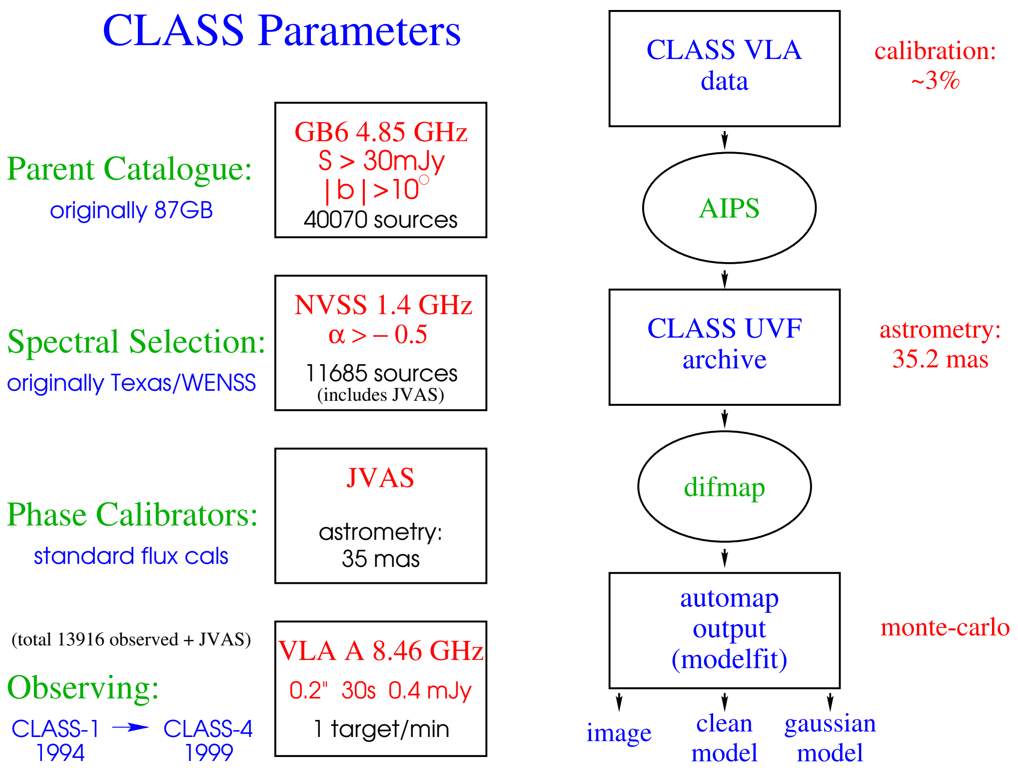
The Survey Sample

To obtain compact multiply-imaged components, we target sources with flat radio spectra (or at least non-steep spectra). We use the convention $S \propto \nu^{\alpha}$ where ν is the frequency of observation. We classify as steep-spectra those sources with spectral index $\alpha < -0.5$ between 4.85 GHz and a lower frequency. Because CLASS has been carried out in three distinct phases, the selection criteria have evolved along with the survey. There have been two major changes in the CLASS selection criteria: the parent sample selected at 4.85 GHz has been updated from 87GB [5] to the GB6 [6] version of the Green Bank Survey, and in addition, the spectral selection versus a lower frequency has evolved from using the Texas [22] and preliminary WENSS [20] survey to the completed WENSS survey and NVSS [3]. The endpoint of this evolution is a robust sample using GB6 with sub-samples spectrally selected on WENSS or NVSS.

The GB6-targeted, NVSS spectrally-selected survey is designated as the "CLASS-NVSS Statistical Sample". At this time the statistical sample consists of 11685 targets with a GB6 flux density of 30 mJy or more, an NVSS source within $70''$ of the GB6 position, and a spectral index $\alpha \geq -0.5$ versus NVSS. The remaining sources that make up the statistical sample will be observed in the CLASS-4 run scheduled for August 1999.

VLA Observations

Two independent IFs of 25 MHz bandwidth (or 50 MHz with WENSS positions) were centered at 8.415 GHz and 8.465 GHz (average 8.44 GHz) for CLASS-1 and CLASS-2. In CLASS-3, which was observed in its entirety using NVSS positions and 50 MHz bandwidth, the IF band centers were moved to 8.4351 GHz and 8.4851 GHz (average 8.46 GHz) in line with NRAO recommendations to avoid RFI. For all CLASS observations, an on-source dwell time of 30 seconds was used, with 3.3-second integrations. A compact source from the JVAS calibrator list was observed after every n-th target source for phase calibration, where n was chosen based on the weather conditions prevalent during the session (for CLASS-1: n = 14; CLASS-2: n = 8; CLASS-3: n = 10–12). The JVAS calibration sources have rms position errors in each coordinate of 12 mas, so the resulting CLASS source positions

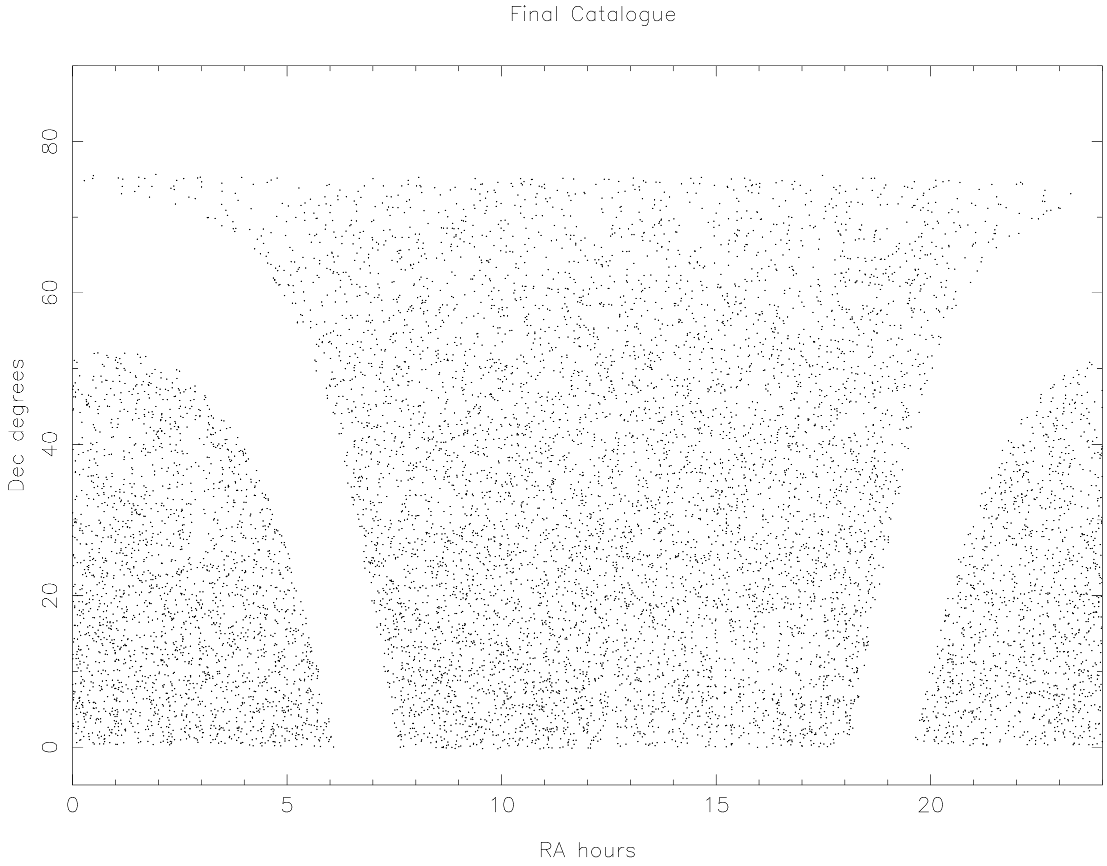


should have accuracies of about 20 mas (in stable observing conditions) and hence should themselves be useful as potential phase calibration sources. We were able to observe one target source per minute, including the overhead from observing calibration sources and slewing between sources.

Analysis Pipeline

The initial editing and calibration of the data was done using AIPS following the standard procedure:

- manual examination and editing of the calibrator data (TVFLG)
- set flux scale using standard calibrators (SETJY)
- solve for gain solutions on calibrators (CALIB)
- check gain solutions and re-edit if necessary (SNPL)
- interpolate gain solutions onto dataset (CLCAL)
- examine and edit CLASS source data for RFI or bad points (TVFLG)
- apply calibration to CLASS sources (SPLIT)
- output UV-FITS files to disk (FITTP)



We have specified the relevant AIPS tasks in parentheses. After carrying out the above procedure, we have the calibrated UV-FITS files for each target source.

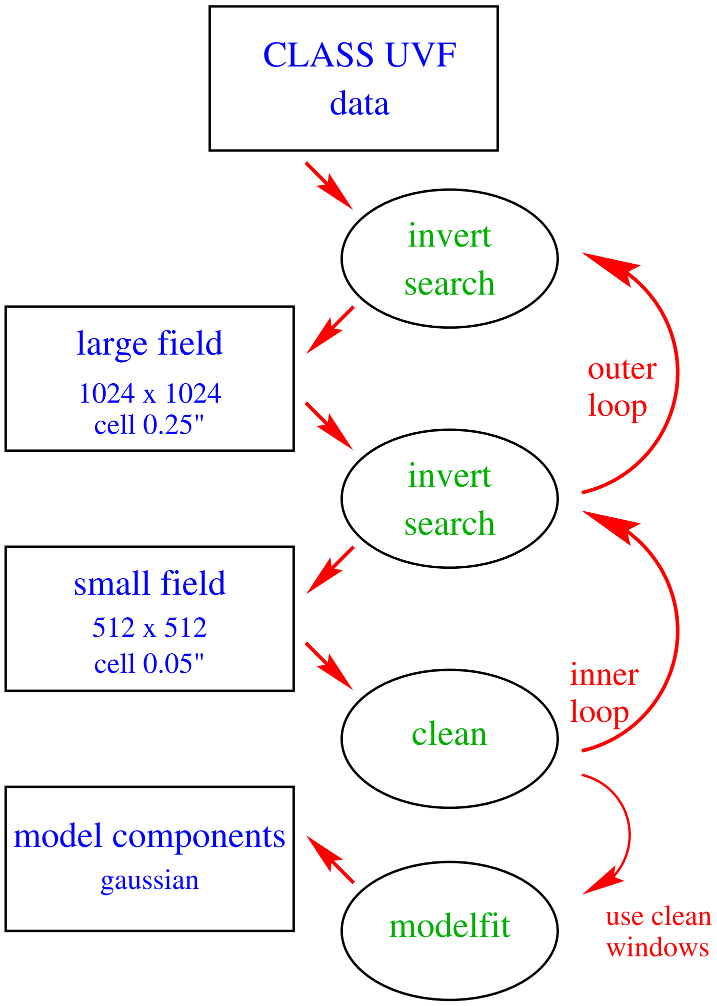
A cross-check of sources that were observed twice during the CLASS sessions and calibrated independently gives an rms position difference of 35.2 mas. This is in line with our expected uncertainties due to the JVAS position errors.

Automapping

The *automap* algorithm can be outlined as follows: (1) Primary Cycle – find peaks in large image above some SNR cutoff; (2) Secondary Cycle – move to location of peak, make small image, find peaks in small image and create CLEAN window; (3) Tertiary Cycle – deconvolve and self-cal iteratively. The locations of the peaks (and thus the clean boxes) are stored for later use.

The SNR cutoffs in the search and field maps were input parameters to the procedure, with SNR of 8 and 10 respectively adopted for CLASS. The data products of the auto-mapping procedure outlined above are the CLEAN model, the set of CLEAN windows, the list of MODELFIT components, and the log-file generated by DIFMAP containing the commands executed plus output information from the noise tests (this log-file can be executed as a script in DIFMAP reproducing the original results).

The limitations of this algorithm include a limited search field (only $128''$ square around

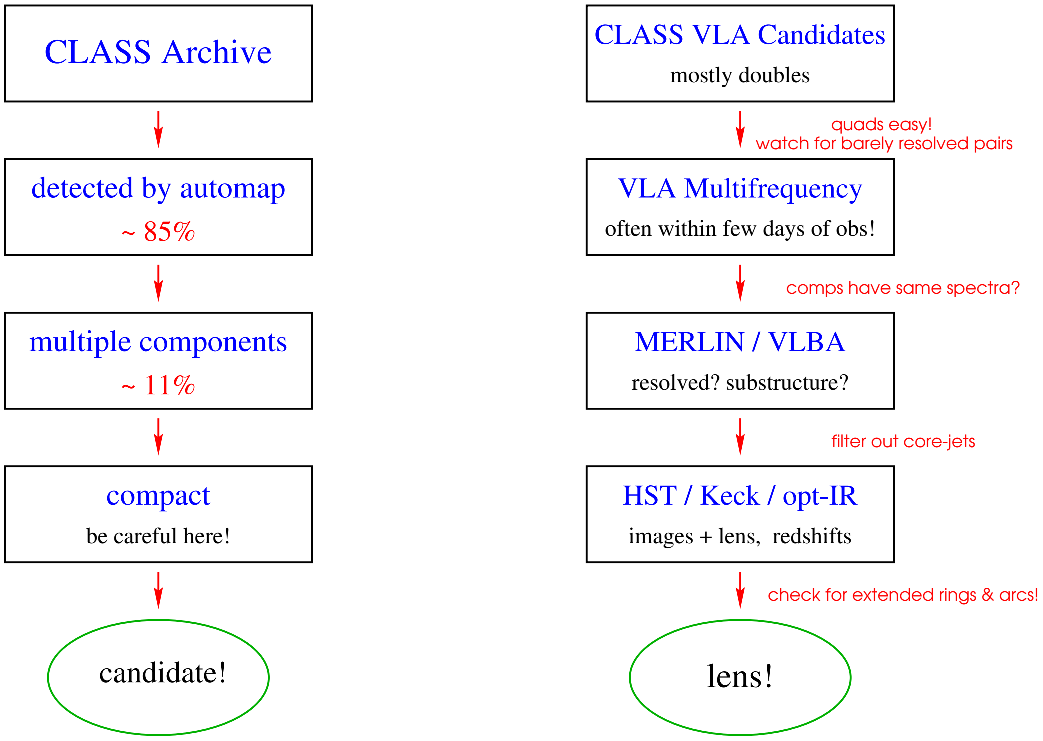


the pointing center), a relatively conservative search SNR limit (8σ to avoid many spurious detections), and dynamic range problems (often spurious multiple components are found on sidelobes from bright sources). However, the automatic mapping has proved to be a reliable method of finding the best candidates quickly. When necessary, questionable images have been re-made manually. This was necessary for only a small fraction of the total.

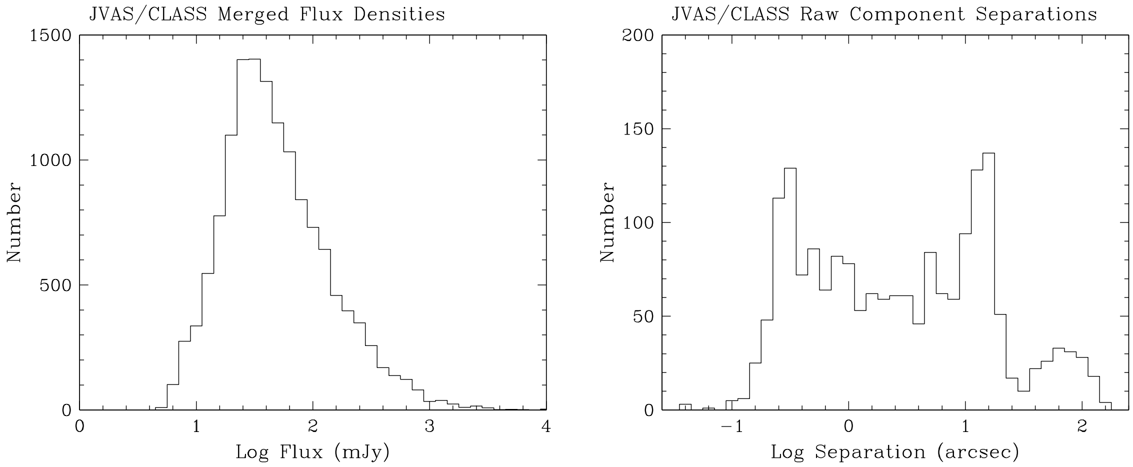
Because the goal of CLASS is to identify multiple-image lens systems with compact components, it is crucial that we quantify the effectiveness of our automapping procedure in finding these objects through a Monte-Carlo testing procedure. A grid of models with two point sources of varying separations, flux ratios, and peak-to-noise ratios were simulated and passed through the DIFMAP script. The script was shown to perform well in expected range of interest.

Candidate Identification and Follow-up

We have adopted the Gaussian MODELFIT results as the best representation of the DIFMAP analysis. Each component has a best-fit position, major axis size, elliptical Gaussian axis ratio and position angle. In addition, uncertainties for the fitted quantities are evaluated from the covariance matrix. These quantities can then be filtered to select candidates with multiple components, and further filtered to find those with multiple compact components.



The raw statistics of the entire JVAS/CLASS sample flux densities (all components of each source merged) and maximum component separations (for all multiple component sources) are shown below:



CLASS Results

From this list of around 1000 multiple sources the 10's of lenses must be found! So far, CLASS has discovered 11 new radio-loud gravitational lens systems and at least one probable binary AGN (quasar). These are listed in the table below. In addition, there are a number of candidate lenses still being followed-up by the team.

Confirmed & Candidate JVAS/CLASS Lenses (DRM 20Jul99)

Survey	Name	# images	$\Delta\theta''$	z_l	z_s	lens galaxy	Refs
			confirmed lenses				
JVAS	B0218+357	2 + ring	0.33	0.68	0.96	spiral	[17], [1]
JVAS	MG0414+054	4	2.09	0.96	2.64	elliptical	[7]
CLASS-1	B0712+472	4	1.27	0.41	1.34	spiral	[9]
CLASS-2	B0739+366	2	0.54	?	?	?	
JVAS	B1030+074	2	1.56	0.60	1.54	spiral	[24]
CLASS-2	B1127+385	2	0.70	?	?	?	[11]
CLASS-3	B1152+199	2	1.56	0.44	1.02	?	[16]
CLASS-3	B1359+154	4	1.65	?	3.24	small group	[16]
JVAS	B1422+231	4	1.28	0.34	3.62	?	[18]
CLASS-2	B1555+375	4	0.43	?	?	?	[13]
CLASS-1	B1600+434	2	1.39	0.42	1.59	spiral	[8]
CLASS-1	B1608+656	4	2.08	0.64	1.39	spiral	[15]
CLASS-1	B1933+507	4 + 4 + 2	1.17	0.76	?	?	[21]
JVAS	B1938+666	4+arc	0.93	?	?	?	[10]
CLASS-2	B2045+265	4	1.86	0.87	1.28	?	[4]
CLASS-2	B2319+051	2	1.36	0.62	?	?	[14]
			probable lenses				
JVAS	B2114+022	2 or 4	2.57	0.32 & 0.59	?	?	
			probable binary quasars				
CLASS-2	B0827+525	2	2.82	?	2.06	none?	[12]

CLASS Data Products

It is planned to release the entire CLASS database as soon as the survey is completed, uniformly calibrated, and verified. This will likely occur in late 1999. Because the majority of CLASS sources are unresolved by the VLA at X-band in A configuration, the survey is goldmine of potential phase calibrators for other observations. One of the primary data products of CLASS will be a comprehensive catalog of calibrators (like JVAS). In the meantime, if there is something specific from the survey that you need, contact the author. For details, see the UPenn CLASS page: *http://www.physics.upenn.edu/myers/class.html*.

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