AIPS, THE VLA, AND THE VLBA

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Abstract. At this writing, the AIPS package has been in active development and use for over 23 years. It is still the software of choice for all phases of data reduction for the Very Large Array, the most productive ground-based telescope in the world. It is the primary reduction system for most Very Long Baseline Interferometry including the VLBA and has been used to reduce data from other radio interferometers and single-dish telescopes as well as data taken at other wavelengths. The history and general structure of this software package are reviewed and a number of the scientific achievements for which it has been used are summarized.

1. Early history

The National Radio Astronomy Observatory was established in 1956 for the purpose of building large radio telescopes and operating them as a service to the world's astronomers. The first telescopes built, a 300-foot diameter transit telescope and an 85-foot and a 140-foot fully steerable telescope, were very productive. However, particularly with the receiver technologies of the 1960s and 1970s, these tended to produce data at relatively low rates. Such data required a modest software effort at most and much of the programming was left to the visiting and staff scientists.

Even in the 1950s however, it was realized that a radio interferometer was needed in order to achieve high sensitivity and spatial resolution. Preliminary design work was begun on the Very Large Array as early as 1960

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(Heeschen 2000). Proposals for the VLA were issued in 1967 and 1969 and first funding for its construction was received in 1972. Construction was completed in 1981 (Thompson *et al.* 1981).

In order to acquire experience with interferometric receivers, correlators, observing, and analysis, a second 85-foot telescope, this time movable, was constructed and first fringes were obtained in 1964. By 1965, serious scientific results from the Green Bank Interferometer were being published; see Hjellming (2000) for a review. Software for the new interferometer was originally written by the scientific staff, and a rather significant package of programs was developed. Eventually, maintenance and development of this package was assumed by the Computer Division.

The software needs for the proposed VLA were underestimated by enormous factors in the proposal stage and continued to be severely misjudged throughout the construction phase, despite the programmers' name for the VLA ("Data Inundation Device"). Numerous committees met and, each time, the number of super computers required for VLA data calibration and analysis went up. Finally, early in 1979, it was decided to begin a software effort in Charlottesville, Virginia, the site of the NRAO's headquarters. It was felt that such a software project would be more immune to the day-to-day needs of the telescope which would, of necessity, plague the parallel software efforts being conducted at the VLA site in New Mexico.

The design discussions for this project, which had been going on for some time, had come up with a list of basic criteria for the new system. The first of these criteria was that the software had to be transportable across both space and time. Although it was assumed that observers would come to NRAO to do the main reductions of their data, many of them would have obligations at their home institutions that would prevent them from completing their analysis during their visits. Furthermore, it was very clear that the NRAO could not afford the computing resources that the instrument demands. If a software package may be run at the user's home institution, then the usage time and compute power available to the astronomer are increased significantly. The software needs to be general and flexible to allow for changes in instrumentation at the VLA and for use on data from other telescopes. The software must be interactive in order to allow the user to determine the progress of the reductions and to discover, and point out to the software, interesting regions within the data. Given the large volumes of data, the software must be efficient and make as good use of the computer's capabilities as possible. It should be "friendly" — relatively easy for beginning users and yet powerful for advanced users. There should be easy access to the system both for multiple interactive users and for users with long, batch-like computations. In order to survive over time and changes in personnel, the system must be well documented and there must be uniformity in coding standards, conventions, service routines, and the like. These criteria form the basis of the system we now know as AIPS (Astronomical Image Processing System).

I have written two review articles, one covering the history of AIPS' first 10 years in some detail (Greisen 2000) and one for a summer school using AIPS as a tutorial example of system design (Greisen 1988). The software effort began in the middle of 1979 using a ModComp computer equipped with a Floating Point Systems AP120B array processor and an International Imaging Systems M70 television display device. This computer used 16-bit word addressing, which forced all programs to be smaller than 128 kilobytes (after much overlaying). In fact, the oversight committees wanted us to make the programs half that size so that they would run on Digital Equipment Corporations PDP 11s. We never made it that small. At the end of 1979, we acquired a DEC VAX 11/780 with an AP and TV, which gave us our first taste of a modern software development environment.

When we began the project, "portable" software was a package of a few thousand lines of Fortran that could be brought up on another computer system in under a year. With AIPS, we achieved immensely more than that, but at the cost of some serious complexities in the software. Fortran 77 was not widely available and PDP 11's had hardware unable to meet the requirements of that language. Therefore, we used Fortran 66, an ill-defined language with numerous portability issues which were solved but required significant effort from the programmer. This early form of AIPS eventually ran on machines ranging from the ModComp and VAXes with and without array processors to UNIX desktop computers, IBM mainframes, and even Cray supercomputers.

AIPS had to contend with political matters. In its earliest days, there was an oversight committee made up primarily of scientists actually stationed at the VLA site. They were understandably nervous about a system being built 2000 miles away by a group over which they had little control. By renaming the project RANCID (Radio Astronomy Numerical Computation and Imaging Device) for a year, we managed to get people to take us less seriously long enough for us to get the project well underway. When the Director had to explain to his oversight committees the expenditure of one million (1979) dollars on this project, we renamed it AIPS, which was at least a little more serious.

Quite a number of people have made significant contributions to AIPS over the years. Of these, Bill Cotton is by far the most important. His early work on high-performance imaging and later design and coding of the calibration and object-oriented software make AIPS what it is today. David Brown, Phil Diamond, Chris Flatters, Walter Jaffe, Pat Murphy, and Don Wells should also be mentioned here, while a more complete cast of

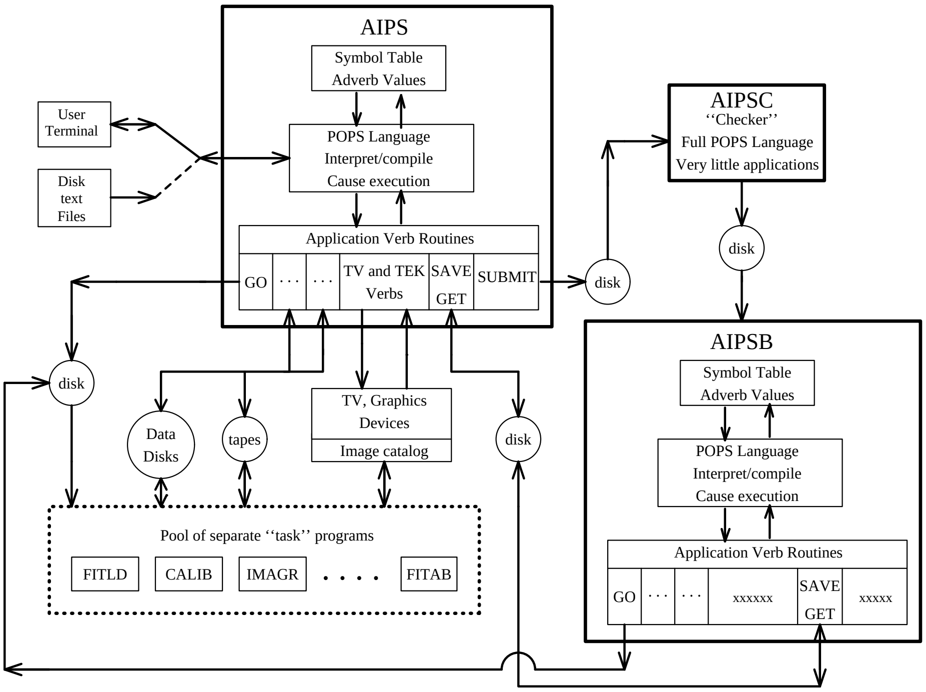

Figure 1. Block diagram of AIPS from a user point of view. Various communications paths are shown among the main interactive program, `AIPS`, the batch program `AIPSB`, and the collection of separate tasks.

characters may be found in Greisen (2000). At its peak, development and support of AIPS reached about 7 full-time employees for a short period; 3–4 was more typical, and the current number is between 1 and 2 for the combination of development and user support.

2. Structure of AIPS

AIPS was begun at about the same time as FITS was designed — see Greisen (2002) in this volume — and was the first system profoundly affected by FITS concepts. The internal header format of AIPS is a binary representation of a FITS header and the disk structure consists of a header file, an image or uv-data file, and "extension" files which are mostly tables, plot files, and history files. It is now written in ANSI-standard Fortran 77 with some system-dependent and X-Windows routines written in ANSI-standard C. Certain system functions are performed by scripts (now mostly Bourne-shell UNIX scripts) and recently some have been recoded and extended using Perl, particularly the installation script.

AIPS consists of a main program with which the user interacts, also called `AIPS`, plus a large set of separate programs which are started by the main program and which may also interact with the user. The structure is illustrated in Fig. 1. `AIPS` takes input interactively from the user or from a text "RUN" file. The input is interpreted by a simple, but essentially complete, computer language called POPS which allows the usual mathematical, logical, and string operations and the creation and execution of procedures which may call other procedures. Some application functions, such as interactive display functions, are run within the main program. Heavily computational operations are run synchronously or asynchronously in separate programs called tasks. These tasks may be developed and run with no modification to the main program. The only interaction between `AIPS` and the task is through a well-defined interface of parameters, called adverbs, whose values are set by the user in `AIPS` and then sent to the task at start-up time[1] and, of course, through any changes that the task may make to the data on disk. Tasks may also be interactive, in which case they run synchronously and retain control of the user input terminal (now usually an xterm window) and other interactive devices such as the TV display. The TV and graphics displays are now done with programs that emulate the earlier devices. XAS emulates the full IIS M70 on X-Windows screens that are capable of full TrueColor display and implements the image catalog as well, while line graphics is done with a Tektronix emulation found in standard xterm and other terminal programs. The ability to run a full batch queue with a batch-control version of `AIPS`, called `AIPSB`, was used heavily in the early days and still remains available.

An image processing system must perform operating-system like functions. It must, for example, be able to create, open, write, close, truncate, reopen, read, and delete disk files. It must know the current time and date, talk to display devices, enable multiple processes to communicate, and translate between internal and external binary data representations. In order to do this, while keeping the majority of the code portable, we invented[2] the concept of a "virtual operating system" or, more generally, "virtual device interface." In AIPS, we designed what we thought an operating system should look like and then forced each system to behave that way with a layered set of "Z" routines. The layers of Z routines are structured to achieve maximal reuse of code, so that routines that work for most systems are at the top and then branches separate, for example, VMS and UNIX, then separate flavors of UNIX, and only then the various vendors. The other virtual device interfaces in AIPS are for array processors, interac-

[1] The option to allow tasks to return adverb values to `AIPS` was finally added in 2002.

[2] Others also invented these concepts independently and much study in computer science was devoted to them, all unknown to us.

tive (TV) displays, and graphics displays. In the early days, at great effort, we achieved barely tolerable performance on intensive computational tasks by writing special code for our array processors. That code was separated out as "Q" routines and an emulation of the array processor was coded to use the host CPU directly. Today, array processors cost too much to code and all applications use the pseudo-array processor software. Because these subroutines isolate intensive computational operations, compilers are often able to create very efficient executables from them. In the early days, there were a large variety of TV-like image displays. By designing an interface to an ideal display (actually much like our initial IIS M70), we were able to code "Y" routines for a large number of routines including the ones for `XAS`, the X-Windows emulation of the IIS M70, used by all current AIPS installations. The graphics functions are isolated by having all plot programs call a limited set of graphics routines which write their plot commands into disk files attached to the primary image or uv-data file. Programs for each possible graphics display (*e.g.,* TV, Tektronix, PostScript printer) were then written to interpret the plot file to the particular output device.

AIPS has been widely distributed, reaching all continents and most states in the U.S. We used to poll known sites annually, but gave it up after 1990. Compiling the poll was an enormous job and desktop workstations made our standard questions (how many users, what fraction of the CPU time for AIPS, etc.) less meaningful; see Bridle and Nance (1991) for details of the last formal poll. These polls and our current informal registration system have tracked the move from VAX VMS to SUN workstations to PCs running Linux and the continued increase in users of, and the compute power used for, the software. Information about AIPS, and the code itself, is available at no charge from `http://www.aoc.nrao.edu/aips`.

3. Later history

Tests in the late 1980's revealed that compilers produced less efficient, and sometimes incorrect, code when forced to use the Fortran 66 dialect of AIPS, rather than a standard Fortran 77. That language was finally available everywhere and offered numerous advantages including true character strings, `IF-THEN-ELSE` constructs, and defined data sizes which greatly simplified the calling of subroutines and the use of data structures. We therefore froze AIPS for nearly 18 months and completely overhauled the code, releasing the new version finally in October 1989. It was in this same period that the VLA decommissioned its old DEC-10 with its familiar VLA calibration software. A large number of users then found themselves dependent on the new, and largely untried, calibration software in AIPS. That package was designed with more general interferometers, particularly very long baseline (VLBI), in mind and, hence, was unfamiliar to VLA observers.

An unfortunate combination then occurred of the discontent over the new calibration package, the long-standing discomfort caused by dependency on software generated elsewhere, and various feuds that had arisen over software issues, particularly AIPS' adherence to strict coding and generality standards. Meetings were then held to determine the future of NRAO's software effort. These meetings concluded that AIPS should be overhauled substantially, one major piece at a time. Nonetheless, the new head of the Computer Division Geoff Croes decided in 1990 to create a new software package using the new `C++` language. I will not attempt to describe that project, called `aips++`, here. It is a major software project, involving an international consortium, and a significant effort in manpower, and is aimed at various aspects of telescope control and data handling in addition to basic synthesis reduction. While `aips++` is not quite ready for production use in reducing VLA and VLBA data, it has already created very useful libraries, special-purpose production packages, and interesting new algorithms. More information is available at `http://aips2.nrao.edu/`.

Croes wrote in the April 15, 1991 AIPSLetter: "A major consequence of this plan is that AIPS has been frozen. Current software development in AIPS is limited to improvements needed in the short term for VLBA calibration and certain experimental imaging tasks.... the manpower we have available to support AIPS has been dramatically reduced ..."

Despite this edict, there have been significant developments in AIPS in the last 11 years. AIPS was converted to run across Local Area Networks, freely sharing disks, tape drives, and displays between computers. The X-Windows display program was overhauled to support TrueColor and to be self-describing. Bill Cotton wrote a large package of data interface routines based on the concepts of object-oriented methodology (Cotton 1992). This package made possible the construction of tasks much larger than those which were maintainable under traditional software methodologies. `IMAGR`, to be described in the next section, is a major example. In addition, significant, nearly revolutionary, improvements have been made in all phases of the package from data loading, editing, and calibration to imaging, display, and data storage. However, because of its putative limited lifetime and lack of manpower, the AIPS group has not carried out major overhauls of whole areas of code/design. It has also become increasingly difficult to attract and retain employees in the group.

4. Algorithmic achievements

The main role of a package like AIPS is not to experiment with new algorithms. Instead, it is to deliver a reliable and comprehensive package of algorithms in a form that can be used by a wide range of scientists around the world. This, AIPS has done. Nonetheless, users have been drawn to the package on several occasions by algorithms that had their first widely available implementation in AIPS.

Images produced by an interferometer are convolved with the Fourier transform of the data sampling, which is a quite complicated function. Högbom (1974) invented an iterative algorithm called Clean for deconvolving such images and Clark (1980) not only invented an efficient implementation of Clean, but also made his code for the array processor available to the AIPS group. This was the only widely available implementation of this particularly efficient algorithm. Cotton and Fred Schwab devised an enhancement of this algorithm which periodically subtracts the Clean component model from the visibility data and makes new residual images. Since this allows images to be Cleaned almost to their edge and permits numerous corrections to be made in the process, the Cotton/Schwab Clean is the one used by `IMAGR`.

Images produced by an interferometer are also affected by errors in the gain and phase calibration, often due to short-term changes in the atmosphere or ionosphere. If the model of the source were perfect, then any difference between the observed and model visibilities must be due to calibration error. Since the calibration generally is assumed to be antenna dependent, there are only N gains to be determined from the observations made on $N(N-1)/2$ antenna pairs. If the number of antennas is significant, this is a heavily over-determined problem which means that errors in the source model will not overly degrade the gains derived. This "self-calibration" may be iterated with re-imaging of the corrected data until the solutions converge. This algorithm was first implemented by Schwab (1980) in AIPS.

The effects of Clean and self-calibration on a VLA image are illustrated in Fig. 2, which shows a radio galaxy observed by Clarke & Vogt (2002). Without Clean and self-calibration, the jets of this (and most) galaxies would not be visible.

The task `IMAGR` first appeared in 1995. In its initial release, it implemented numerous options for data weighting including the "robustness" concept (Briggs 1995) which allowed an optimal balance of spatial resolution and signal-to-noise to be achieved. Images produced by an interferometer are correct on the celestial sphere, not the two-dimensional planes on which they are usually computed. Beginning in 1998, `IMAGR` is able to do the imaging on numerous small two-dimensional planes covering the desired field of view and each tangent to the celestial sphere. Although this means of correcting the "3D" problem was described by Cornwell & Perley (1992), it became available to a large number of users only with its implementation

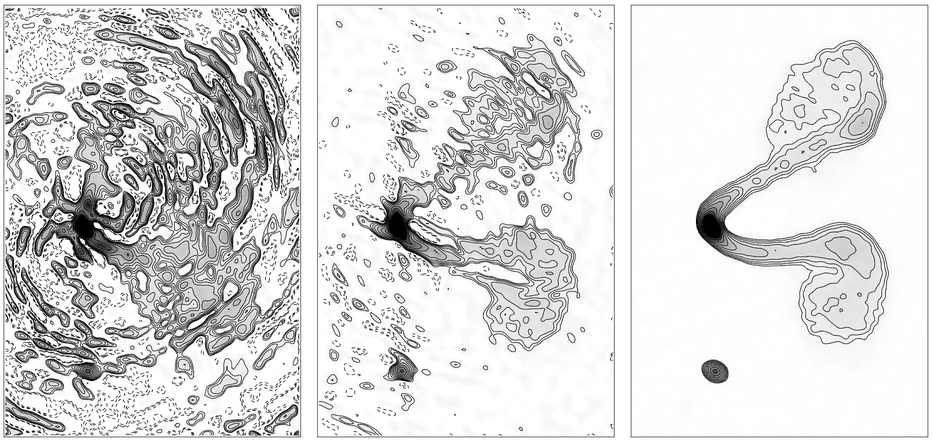

Figure 2. Clarke & Vogt (2002) images of the radio source IC 708 in the cluster of galaxies known as Abell 1314. The "dirty" image at left has a peak-to-rms ratio of 67. For the Cleaned image in the center that ratio is 262, while it is 2061 for the self-calibrated and Cleaned image at right. The same contours are drawn in each image.

in AIPS. Without this option, the very wide-field imaging now done with the VLA at wavelengths $\geq$ 21 cm would not be possible. `IMAGR` now also implements the multi-scale algorithm described by Holdaway & Cornwell (1999). See Fig. 3 for an example. Since AIPS is a complete system, images made with these options produce source models which may be used throughout the package for such operations as self-calibration.

Experiments with maximum entropy related deconvolution techniques by Cornwell & Evans (1985) led Cornwell to place the task `VTESS` in AIPS. This task is still used as a benchmark by which other multiple-pointing ("mosaicing") deconvolution algorithms are measured.

In 1981, NRAO began design studies for an array of telescopes to be spread across the United States and operated as a single very-long-baseline telescope. Initial funding for VLBA construction was received in 1984 and construction was completed in 1993 (Napier, *et al.* 1994). On May 6, 1992, the VLBA Correlator produced its first fringes. Within 12 hours and 2000 miles away, AIPS read, sorted, and plotted these data with correct annotation. AIPS has been the main software system of the VLBA and one of the primary systems for all VLBI reductions. In part this is due to an algorithm designed by Schwab & Cotton (1983) to use data from all baselines simultaneously to make the array maximally coherent, finding corrections on an antenna basis rather than on a baseline basis. Calibrations of greater reliability and accuracy are determined in this fashion and may be found for much weaker sources than previously.

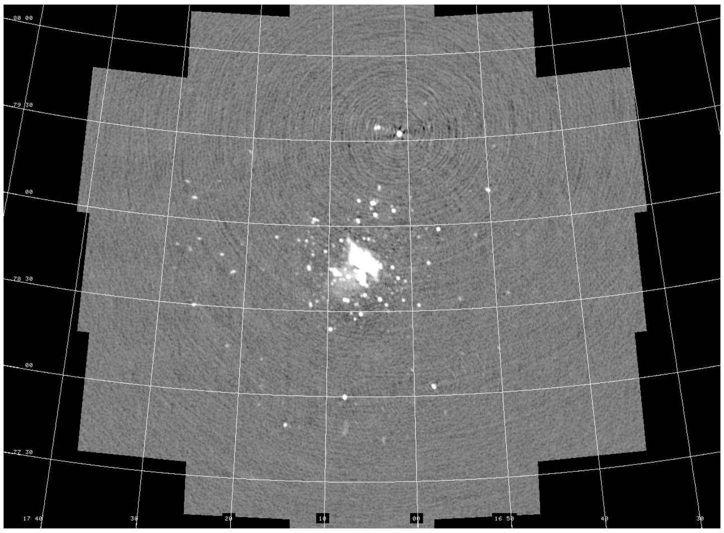

Figure 3. Clarke & Ensslin (2001) data on galaxy cluster Abell 2256 from the VLA's most compact configuration. The image was constructed with 19 facets each tangent to the sphere and then re-sampled into a single plane for this display. The primary beam of the individual antennas in the interferometer covers only a little more than one of the coordinate "squares," but all 19 must be Cleaned to remove sidelobes of objects to which the VLA responds.

5. Scientific results

According to publication statistics maintained by the NRAO, the VLA has been the most productive ground-based telescope, lagging only the Hubble Space Telescope and IRAS in overall publication rate. (See also Benn & Sanchez (2001) for publication statistics heavily weighted by citations.) The VLA has been used for projects touching all areas of astronomy and AIPS was used for part or all of the data reductions in almost every case. It is not possible in this limited space to even list the major achievements of the instrument; the projects described here are just a nearly random sample influenced by ready availability. The NRAO is developing an image gallery at `http://www.nrao.edu/imagegallery` which includes a wide range of images produced by NRAO's telescopes. The book *Radio Interferometry: The Saga and the Science* published by NRAO has review papers covering many of the important research areas.

The VLA first made a splash with images of radio galaxies such as that shown in Fig. 4. The high angular resolution and significant dynamic range achieved allowed the tubes of plasma, by which energy and matter are transmitted from the central engine to the radio lobes (the "jets"), to be studied for the first time. Images made in the linearly polarized emission

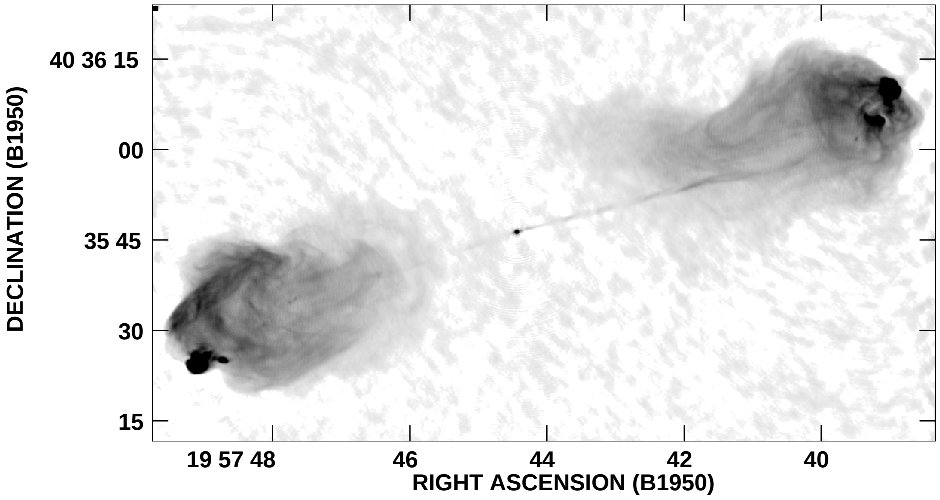

Figure 4. Perley *et al.* (1984) image of the radio galaxy Cygnus A at 4.525 GHz with 0.4 arc second resolution.

permitted the structure of the magnetic fields to be determined. Details in the structure of the radio lobes, suggesting how they are formed, were also revealed; see Owen *et al.* (2000) for an example. The above-mentioned web site has links to Alan Bridle's marvelous collection of images and information on radio galaxies; see also Bridle (2000). The VLBA, with its very high spatial resolution, may be used to study the inner workings of these radio galaxies and quasars (*e.g.,* Zensus *et al* 2002 and Zensus 1997). One of the more important results from the VLBA is a direct measurement of the distance to the active galaxy NGC4258 from measurements of the orbital motions of gas around its nucleus (Herrnstein *et al.* 1999). These data provide a direct measurement of the mass of the central object in that galaxy and are the most direct proof yet of the existence of black holes.

The VLA has also been used for observations of the interstellar medium, particularly the neutral hydrogen emission, of normal galaxies. Fig. 5 shows an example of the total hydrogen content and velocity field of the galaxy NGC6503. Van Gorkom (2000) provides a review, while the NRAO image gallery has a large number of images from this area of research.

The VLA and VLBA have also been used extensively for observations of objects within our Galaxy. An early image that strained our computing resources is shown in Fig. 6. Supernova remnants have many moving knots of small angular scale, but the bulk of the emission comes from a relatively smooth region of significant angular size which is difficult for interferometers to image. The Galactic Center is another region which is filled with both

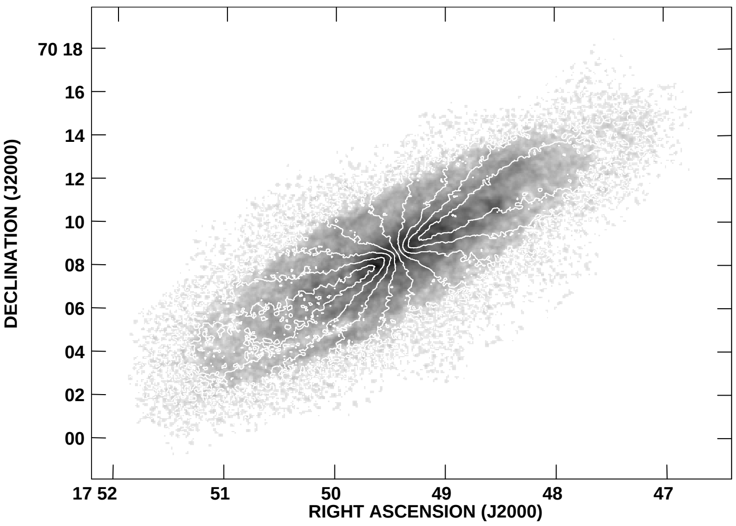

Figure 5. Greisen & van Moorsel unpublished image of the total neutral hydrogen (gray scales) in the galaxy NGC6503 with contours of constant velocity (separated by 25 km/sec) made with the VLA at 14 arc second resolution.

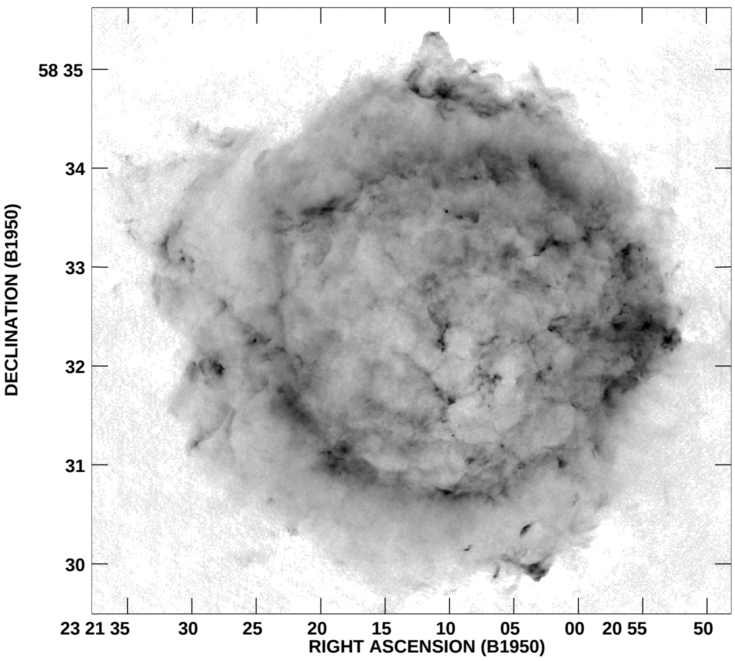

Figure 6. The supernova remnant Cassiopeia A at 1.38 GHz (Anderson *et al.* 1991).

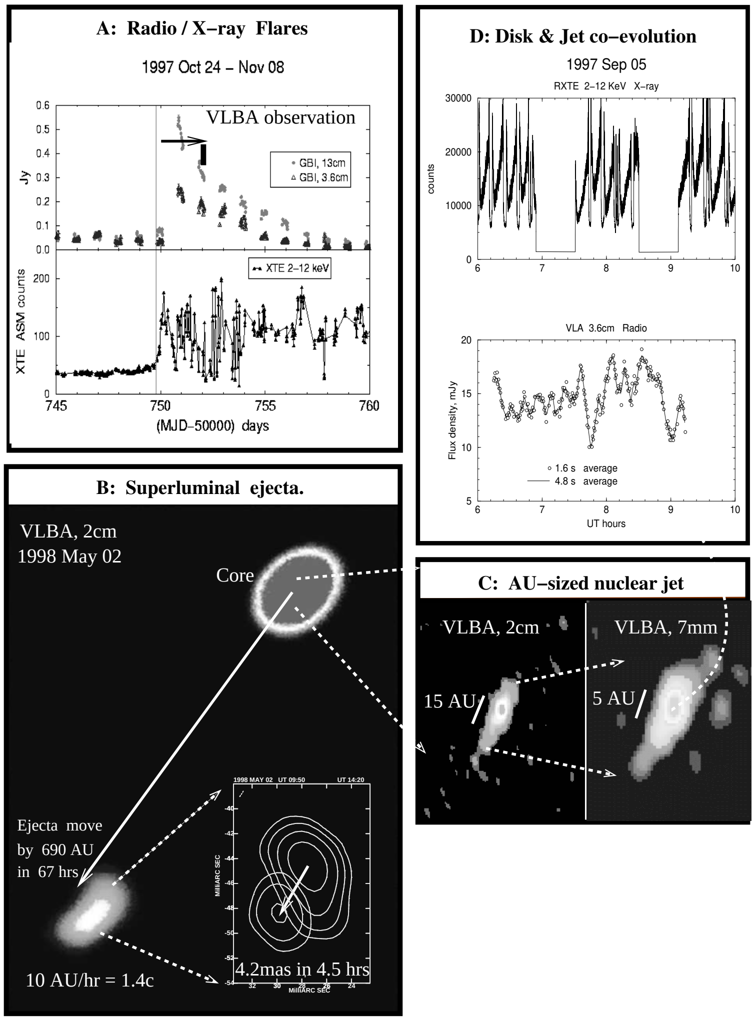

Figure 7. Dhawan *et al.* (2000) images of the rapidly varying Galactic micro-quasar GRS 1915+105.

large-diameter sources as well as incredible narrow arcs and other emission features which appear to trace magnetic fields. The optical light from the center is completely obscured, making radio wavelengths the main source of information about the heart of our galaxy. See Morris (2000) for a review of the VLA's contributions in this area. Most normal stars are relatively weak radio sources, but the VLA has made important contributions to their study (White 2000). Most small-size galactic X-ray sources arise in binary systems in which one star dumps its material onto a compact star, presumably a black hole, neutron star, or white dwarf. These objects can be highly variable, changing on time scales of seconds to minutes while ejecting blobs of charged particles and magnetic field at *apparent* speeds in excess of the speed of light (Mirabel & Rodriguez 1999). GRS1915+105 has been observed nearly simultaneously in X-rays and with the VLBA. The results are summarized in Fig. 7 (Dhawan *et al.* 2000).

The VLA has also been used to study Solar System objects. Muhleman *et al.* (1995) review radar observations and de Pater (1990) reviews synthesis observations of planets. Bastian *et al.* (1998) review observations of the Sun in its active phases.

The two major surveys done by the VLA, the low resolution NVSS (Condon *et al.* 1998) and higher resolution FIRST (Becker *et al.* 1995), have provided source material for many statistical studies of radio sources of various kinds.

AIPS has also been used for single-dish data when the data rates have gotten large. This first arose with all-sky surveys conducted with the Green Bank 91-m (300-foot) telescope at 1.4 GHz (Condon & Broderick 1985 and 1986) and then at 4.85 GHz (Condon *et al.* 1994). AIPS was then used with millimeter-wavelength data taken by the 12-m telescope in Tucson in the popular on-the-fly observing mode. This technique is described by Mangum *et al.* (2000) and scientific results obtained with the 12-m using AIPS include Womack *et al.* (2000), Arce & Goodman (2000), and Koo (1999). The 12-m was even used in beam-switched on-the-fly continuum mode with the data reduced in AIPS by Liszt & Lucas (1999).

6. Summary

AIPS, the Astronomical Image Processing System, has served the NRAO for 23 years. Its main role has been to put interferometric data calibration, editing, imaging, and display programs in the hands of the users of NRAO's Very Large Array and Very Long Baseline Array, both at the NRAO and at their home institutions. It has also provided useful functionality for data from other radio interferometers, single-dish radio telescopes, and even optical telescopes. With these tools, the users have produced a dazzling array of important and useful scientific results from nearby comets, planets, and the Sun to strange and wonderful objects within our galaxy to powerful radio galaxies and quasars at the very edges of the universe.

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