

23. Radio Astronomy

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Alan H. Barrett

During 1984 the following programs of research on the interstellar medium and star formation were pursued:

1. In an attempt to determine the interaction between the Sgr A molecular clouds and the continuum sources in the galactic center we made observations of the continuum sources at wavelengths of 6 cm and 2 cm with the Very Large Array to supplement our previous spectral line observations of the molecular clouds. The VLA observations revealed both thermal and nonthermal sources which appear to be embedded in the molecular clouds. The results suggest an interaction between the molecular and ionized gas. The thermal sources are at the positions of maximum density of the molecular clouds. We suggest that the clouds are within 10 parsecs of the galactic center, that tidal stripping of the lower density envelopes of the clouds can support an accretion rate greater than 10^{-3} solar masses/year for $\sim 10^8$ years, and thus provide fuel for the energetic physics processes occurring at the galactic center.

2. Considerable attention has been focused in recent years on spiral galaxies with regions of enhanced emission, so-called "hot spots", in their nuclei. Although considerably less luminous than Seyfert galaxies, the hot spots are suggestive of Seyfert morphology. It is unclear if this activity is powered by (1) accretion of material onto a massive compact object, or (2) an episode of rapid star formation confined to a small nuclear region, i.e. a "starburst". The starburst hypothesis accounts for many of the optical, infrared, radio, ultraviolet, and x-ray properties of a large number of galaxies and, thus, is gaining support. The success of the starburst model has led us to study a selection of these galaxies in the 21 cm hydrogen line and the 2.6 mm line of carbon monoxide. Both lines have been detected in a number of starburst galaxies using radio telescopes at Arecibo, Kitt Peak, University of Massachusetts, and the VLA. Preliminary results

suggest that atomic and molecular lines are more readily detected from barred spirals than from field spirals. For example, eight of the ten starburst galaxies we have detected in CO exhibit barred morphology. It is suggested that the rapid star formation may be fed by gas streaming along the bar into the center of the galaxy.

3) The southern Milky Way has been sparsely studied in the 2.6 mm $J = 1 \rightarrow 0$ rotational transition of carbon monoxide because of the lack of facilities. A graduate student has participated in a CO survey of the southern regions of our galaxy using the 1.2 meter telescope of Columbia University and the Goddard Institute of Space Studies located in Cerro Tololo, Chile. Besides studying the general galactic distribution of CO, observations were also taken on local regions of low-mass star formation, such as the Lupus complex. Over 10,000 spectra were taken and the data are currently being analyzed and correlated with optical, infrared, and x-ray data.

23.1 Galactic and Extragalactic Radio Astronomy

National Science Foundation (Grant AST82-14296)

Bernard F. Burke

The distribution of matter in galaxies and in the universe as a whole is being investigated. The primary methods are the study of the deflection of radio and light waves by the gravitational fields associated with large-scale aggregation of matter, and by direct observations of the gravitational interactions of galactic systems.

1) The gravitational lens work emphasizes continued studies of 0957 + 561. This lensed quasar is being monitored at the VLA in a program to measure the time delay between the arrival of wave fronts of the two lensed images. A determination of the time delay could in principle constrain estimates of cosmological parameters, and such studies of many gravitational lens systems will certainly tell us a great deal about cosmology and the distribution of matter on the largest scales.

2) A new program to look for many more gravitational lens examples is under way. We have examined over 3000 sources with the VLA and expect 5 to 10 new examples of gravitational lenses. It turns out that the "snapshot" ability of the VLA makes it far more advantageous to use the VLA to find the candidates, following up later with optical verification, than the other way around. One new gravitational lens system, MG2016 + 112, has been discovered and reported (Lawrence, et al., *Science*, 8, 46), and another triple radio source is most certainly another lensed quasar.

3) VLBI observations of a sample of radio sources showing sub-arcsecond structure are being analyzed for evidence of gravitational lensing on a subsecond scale. Theoretical calculations indicate that lensing by single galaxies should produce many examples of multiple images with

such small separations.

4) The studies of interacting galaxies continues. The NGC 4038/39 work now emphasizes theoretical studies.

The MG survey continues. The first section, covering declinations 0 to 20 degrees, has been completed (C.L. Bennett, 1984, M.I.T. Ph.D. thesis). A new section of the survey, covering declinations 17 to 47 degrees is already 25% complete. No other high frequency survey to date is complete to as low a flux level over as large a region of sky. Studies of properties of this unique sample of thousands of radio sources, addressing such questions as the radio luminosity function, large-scale clustering and radio source evolution, are beginning.

23.2 Jovian Decametric Radiation

*National Aeronautics and Space Administration (Grant NAGW-373 and Contract NAS5-28410)
David H. Staelin, Philip W. Rosenkranz, Tomás A. Arias*

The Planetary Radio Astronomy (PRA) experiment on the Voyager 1 and 2 4) Correlations of radio and optical properties of radio sources continues. Here, the work of Lawrence et al. has generated an exciting new range of projects. The highest priority has been to obtain redshifts of a number of sources (only 21 of the 602 sources studied have measured redshifts). One sharp result of Dr. Lawrence's work is the derivation of a number of measured redshifts needed to distinguish between pairs of models presented by Peacock and Gull (MN 195, 611 (1981)). Strong sources (5 GHz $S > 1$ Jy) cannot do the job, because more sources would be required than exist in the sky; only by going to fluxes in the range 50–150 mJy can there be a reasonable expectation of distinguishing models.

5) The emphasis of the work on VLBI studies of interstellar masers has shifted to H₂O and SiO masers.

6) The continuum VLBI work consists of 4 parts: collaboration with the Brandeis group on polarization studies; 7–mm VLBI techniques, still in developmental stages; low–frequency VLBI at 327 MHz while we prepare a still longer–wavelength experiment; and the new initiative described under (7) below requires VLBI observations in many cases.

7) The morphological and identification work of Lawrence has generated a new class of radio and optical projects. There are 318 point sources, of which 175 have OSS counterparts. Over half of these are almost certainly quasars, and these constitute the largest radio–selected sample currently available. The 92 double sources, mostly having no PSS counterpart, are being examined at other frequencies with the VLA, and searches for faint optical counterparts down to $m \approx 24$ are carried out with the MASCOT CCD at the McGraw-Hill Observatory. There are 46

sources in a category called "core-double". These are doubles with an obvious nuclear source near the mid-point and clearly distinguishable from the "triples" (there are only 15) and will receive immediate optical follow-up. Finally, we are planning to use the Arecibo telescope to reobserve all 1000 sources in our VLA sample at 21 cm to obtain a set of uniform spectral indices. The fluxes will be directly comparable with the 300 ft. 6 cm measurements since the beamwidths are about the same size.

23.3 Jovian Decametric Radiation

National Aeronautics and Space Administration (Grant NAGW-373 and Contract NAS5-28410)

David H. Staelin, Philip W. Rosenkranz, Tomás A. Arias

The Planetary Radio Astronomy (PRA) experiment on the Voyager 1 and 2

spacecraft observed Jovian decametric radio emission in 198 channels distributed over the band from 1.2 kHz to 40.5 MHz. Most prior analysis of this data has been based on 48-second averages of 6-second spectra which have been displayed with limited dynamic range, thus obscuring much structure. These prior analyses have focused on the prominent "arcs" in the frequency-time domain, which have been associated with radio emission having a hollow conical emission pattern near the local electron-cyclotron frequency. Theory suggests that such emission might be produced by magnetospheric currents generated by the satellite Io as it traverses the Jovian magnetospheric field.

During 1984 a few weeks of Voyager data was examined with 6-second resolution and an adjustable dynamic range. The most prominent new phenomenon that has been identified we designate as modulated spectral activity (MSA). This is most evident at frequencies below 1.2 MHz where the spectrometer has higher spectral resolution. MSA is manifest by strong emission over several hundred kilohertz with an intensity which varies approximately sinusoidally in frequency with a period of ~ 100-200 kHz; such patches of emission typically last several minutes and can exhibit stability in the phase angle of the frequency modulation intensity pattern over periods ranging from less than 6 seconds to more than 1 minute.

Two other properties of MSA are of special interest. Sometimes the modulation appears to exhibit a sawtooth pattern suggesting that the modulation might be associated with plasma waves that are to some degree nonlinear or even shocked. There is also evidence for polarization reversal periodic with frequency, where the period is less than 100 kHz. These phenomena are being studied further and documented.

23.4 Long-Baseline Astrometric Interferometer

U.S. Navy - Office of Naval Research (Contract N00014-84-C-2082)

M.I.T. Sloan Fund for Basic Research

Michael Shao, David H. Staelin, John W. Barrett, Lloyd D. Clark, Jr., M. Mark Colavita, R. Walter Holm, Matthew J. Kelly, D. Cosmo Papa

During 1984 significant progress was made in development of the Mark III optical astrometric interferometer which is to be installed at Mount Wilson Observatory in California during 1985. It is a modified and substantially expanded version of the Mark II interferometer which employed two 10-inch siderostat mirrors 3.4 meters apart in a North-South direction. The Mark II successfully demonstrated a two-color technique for measuring and reducing the astrometric effects of the atmosphere over time intervals so brief that the atmosphere could be considered "frozen".

The Mark III instrument is improved in several ways. First, the baseline length has been increased to 20 meters in the North-South direction and approximately 10 meters East-West. Secondly the entire structure is now being mounted on massive concrete pedestals sunk into the ground. Under construction are improved siderostats referenced to these pedestals via five laser beams accurate to tens of angstroms. Improved optics and an improved star tracking mechanism based on a photon camera are also being developed. The long baselines require development of two new vacuum tanks ~ 10 meters long to be housed in a shed 6 x 13 meters. New laser tracking equipment is being developed to monitor the position of the movable delay line inside the vacuum tank with an accuracy of tens of angstroms, even when the delay line is being slewed at velocities up to 0.5 meters per second.

This two-color astrometric instrument is expected to demonstrate wide angle ($\lesssim 10^\circ$) and absolute astrometry with accuracies on the order of 10^{-3} arc second. The limits to astrometric accuracy posed by the atmosphere and by other effects will also be studied.

23.5 Tiros-N Satellite Microwave Sounder

National Oceanic and Atmospheric Administration (Grant 04-8-M01-1)

Philip W. Rosenkranz, David H. Staelin, Alain C. Briançon

The National Oceanic and Atmospheric Administration (NOAA) routinely reduces data from one or two operational polar orbiting weather satellites: these now carry infrared spectrometers and 4-channel passive microwave spectrometers (MSU) for the purpose of mapping the three-dimensional temperature field of the atmosphere at 6 or 12-hour intervals. The purpose of this research program is continued improvement in the utilization of the passive microwave data produced by these NOAA satellites and by their successors. Considerable progress has been

made in developing improved analysis techniques for the next generation advanced microwave sounding unit (AMSU). The AMSU design presently includes 15 channels ranging from 23 to 90 GHz, which image almost the entire earth with 50-km resolution every 12 hours; twelve of these channels are dedicated to sounding atmospheric temperature profiles between the surface and 41-km altitude. A second set of five channels, operating between 90 and 186 GHz, will sound atmospheric precipitation and humidity at several levels with 15-km resolution every 12 hours.

Issues addressed include 1) optimum architectures for operational data reduction systems for AMSU, 2) influence of the choice of vertical representation upon the accuracy of temperature profile retrievals, 3) the potential improvement in retrieval accuracy available through use of multi-dimensional statistics and multi-dimensional retrievals, and 4) the retrieval improvements obtainable through updating the *a priori* statistics based on the continuously observed atmospheric correlation statistics. Preliminary experiments suggest all of these techniques can yield improved sounding accuracy.

23.6 High-Spatial-Resolution Passive Microwave Sounding Systems

National Aeronautics and Space Administration (Grant NAG5-10)

Philip W. Rosenkranz, David H. Staelin, John W. Barrett, Alain C. Briançon, Albin J. Gasiewski, D. Cosmo Papa

The theoretical portion of this effort during 1984 has involved 1) evaluating the potential of aperture synthesis systems for use in geosynchronous orbit for rapid sounding of atmospheric temperature and humidity profiles with ~ 20 – 40 km resolution and 2) continued experiments on the impact of initialization errors on high-spatial-resolution numerical weather prediction models. The initial theoretical analysis of aperture synthesis methods suggests that they should yield ~ 30 –km spatial resolution and ~ 0.3 K rms sensitivity over $640,000 \text{ km}^2$ in a few minutes' time. Preliminary documentation of these results has been prepared.

In the study of the propagation of remote sensing errors in numerical weather prediction (NWP) models, these errors are represented in terms of their wavelengths and vertical structure functions. Following Lorenz (1969) this representation is being extended and quantified by means of a series of experiments performed on the University of Wisconsin primitive-equations NWP model. This model covers the United States with 135.2 or 67.6-km resolution at 10 sigma levels. The error-growth model under development will permit the evolution of initialization errors to be predicted in the spectral domain in a statistical rms sense. The choice of initialization errors will correspond to sensor systems of interest.

Accomplishments in the NWP studies include: 1) techniques have been developed for

successfully initializing the NWP model with a perturbation without stimulating significant gravity waves, 2) two small superimposed initialization errors were found to grow during 9-hour forecasts so as to equal approximately the sum of the two forecast errors resulting from the two separate initialization errors; i.e. superposition largely applies here, 3) the error spectra resulting when the same sinusoidal initialization error is applied to completely different initial atmospheric states were found to be quite similar, and therefore these results show that errors of any spatial scale evolve rapidly into errors of smaller scale, but more slowly into errors of larger scale; the results are quantitatively similar to those obtained theoretically by Lorenz,¹ and 5) a draft manuscript describing these initial experiments has been prepared.

The experimental portion of this effort involved development of a 7-channel imaging 118-GHz spectrometer for sounding atmospheric temperature profiles from a NASA Convair-990 aircraft which will fly over frontal systems starting in 1985. This system will also carry a 53.6-GHz radiometer viewing nadir, and a television camera and video tape recorder for imaging the storm system. The instrument development is approximately two-thirds complete. A swath will be imaged beneath the aircraft as the antenna scans $\pm 45^\circ$ across the flight track with $\sim 7.5^\circ$ resolution and full coverage. These data will support 1) definition and analysis of a potential future geosynchronous passive microwave temperature sounding system employing 118 GHz, 2) efforts to develop improved retrieval techniques for use with future high-spatial-resolution sounding systems such as AMSU, and 3) studies of the meteorological character of severe storms and fronts.

References

1. E.N. Lorenz, "The Predictability of a Flow which Possesses Many Scales of Motion," *Tellus* **21**, 289-307 (1969).

23.7 Video Bandwidth Compression Techniques

Defense Advanced Research Project Agency (Contract MDA 903-84-K-0297)

David H. Staelin, Ali D.S. Ali, Philippe M. Cassereau, Rene G. Cornejo, Anne M. Kirkland

This research effort is directed towards methods of coding at 9.6-56 kbps full-motion video sequences characteristic of videoconferencing. The study of morphological coding techniques was completed; they were found to exhibit instabilities due to interpretation ambiguities, and to yield superior results compared to adaptive transform techniques only for extremely low data rates where the image quality was unsatisfactory.

Transform techniques used at these low data rates usually exhibit unacceptable block noise associated with the boundaries of those image subunits over which the transforms are computed. To remedy this a new transform, designated the lapped orthogonal transform (LOT), was developed. The basis functions for this transform overlap with the basis functions in adjacent

blocks, but retain orthogonality with respect to other basis functions within the same block and within neighboring blocks. This transform is now being applied to motion compensated video compression in combination with adaptive transform coding. A study has also begun to explore the benefits obtainable from using transform codes which adapt to the local morphology of the image.