# 13. Radio Astronomy

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During 1983 the following programs of research on the interstellar medium and star formation were pursued:

1. We conducted a brief survey of molecular clouds in the $5_{05} \rightarrow 4_{04}$ and $4_{04} \rightarrow 3_{03}$ transitions of HNCO at 109.9 and 87.9 GHz, respectively. The lines were detected in seven clouds with typical $\Delta T_A^*$ of a few tenths of a degree, with one notable exception. In the Sgr A molecular cloud the HNCO antenna temperature is 3.1 K, an order of magnitude greater than in the other clouds. On the other hand the $C^{18}O$ spectra do not show a similar increase. The $1_{01} \rightarrow 0_{00}$ HNCO transition at 22.0 GHz was detected at Haystack and supports the view that HNCO is overabundant in the Sgr A cloud as opposed to other molecular sources.

2. We have continued our studies of hyperfine intensity anomalies in the $NH_3$ spectra from some molecular clouds. In collaboration with Prof. G. Winnewisser, University of Köln, we have found 13 sources which are known to exhibit anomalous hyperfine intensities. It is believed the unusual intensities arise from selective trapping of the infrared radiation from the J,K $= 2,1 \rightarrow 1,1$ within the various hyperfine levels making up the transition. The observations can be used to constrain the overall gas density within rather narrow limits, typical values being $10^6 cm^{-3}$. An unusual outcome of these studies is that all sources which exhibit hyperfine intensity anomalies in their $NH_3$ spectra also have $H_2O$ masers. The significance of this is not fully understood.

3. Our studies of the continuum emission from the galactic center region have continued. We have detected a number of sources associated with the $NH_3$ peaks in the Sgr A molecular cloud. Most of the sources are thermal and may be regions of recent, or current, star formation. One source is

nonthermal, crescent shaped, and appears to exhibit polarization with the electric-vector oriented normal to the crescent. This is suggestive of the magnetic field being oriented along the crescent, perhaps serving to confine the crescent.

4. A long-term study of the radio properties of star-burst galaxies has been initiated. These galaxies have a bright nucleus, infrared color excess, and optical emission lines whose full width is less than 300 km/sec. Since these properties correspond to the properties of young, hot stars in extragalactic HII regions, these galaxies have been called "star-burst" galaxies. We have obtained HI spectra at Arecibo from 46 galaxies of this type and CO J = 1→0 spectra from 7 (perhaps 10) of these galaxies. The CO and HI spectra are very similar. Observations of the J = 2→1 CO transition are planned to improve the spatial resolution. We also plan observations of $H_2O$ at a wavelength of 1.35 cm.

# 13.1 Galactic and Extragalactic Radio Astronomy

*Bernard F. Burke*

## Overview

This is a set of broadly-based radio astronomy studies of extragalactic radio sources, being carried out, aimed at understanding the distribution of matter in galaxies and clusters of galaxies, the interactions of the ICM, IGM, and ISM with the relativistic plasma ejected by active galaxies, and to explore the extension of VLBI observations to shorter and longer wavelengths. A major emphasis will be a new set of observations aimed at improving our quantitative understanding of dark matter in the universe.

The largest amount of the research will be carried out at national or quasi-national, research centers. The VLA, the Green Bank NRAO facilities, the VLB network, and the Haystack radio observatory will be principal foci. At the same time, we will be carrying out modest in-house hardware development to allow the pursuit of VLB explorations that otherwise would not be possible. This means that our students can still have an interaction with real hardware, an experience that is not commonly available.

The individual components of the program include the study of (1) interacting galaxies, (2) gravitational lensing, (3) time variations of lensed objects, (4) gravitational distortion, (5) quasar-galaxy pairs, 6) structural studies of radio sources, (7) radio source surveys, (8) 7-mm VLBI, (9) long-wavelength VLBI, and (10) continuation of molecular maser VLBI studies. Radio observations alone are frequently insufficient to address astrophysical problems in depth, and we are planning associated optical observations in many of the above areas: in some cases, through collaborating work with optical observers, but principally through utilization of the McGraw-Hill

Observatory, which we share with Michigan and Dartmouth and which will have a 95-inch telescope in operation in 1985.

For many years it has been common knowledge that the luminous matter in the universe, which is the easiest state of matter to detect, is only a fraction of the total mass that makes up large-scale structures such as galaxies, clusters of galaxies, and the universe as a whole. Any single datum might be discussed, but there is a persistent gap between the dynamical mass and luminous mass determined in practically every case. Historically, the mean density of our own galaxy inferred from dynamical studies has been greater than the density measured by a careful census of starts, dust, and gas, an inequality that has recently been revived by the studies of Bahcall, Ostriker, and their collaborators. One popular explanation at present is the massive galactic halo postulate, which simultaneously provides the missing matter and helps to stabilize the thin population I disk. The outstanding spectrographic work of Rubin and Ford demonstrated clearly that spiral galaxies have remarkably flat rotation curves that are most easily interpreted as evidence for massive halos of dark matter (although alternative models have been proposed, the reality remains that a substantial quantity of dark matter, not distributed like the stars, must exist in spiral galaxies).

Evidence for large quantities of matter in clusters of galaxies has long been recognized by application of the virial theorem to observed motions of galxies in clusters. Although some reservations are in order for some of the most spectacular examples, for example, Pegasus II, with $\sigma_{Nu} \sim 2000$ cm/sec is quite probably more than one cluster, with substantially smaller velocity dispersion within each cluster. There has been speculation that the mass fraction of dark material inferred from the mass-to-light ratio is proportional to the size of the system: the mass-to-light ratio is apparently 5 to 10 in the case of galaxies, some integral multiple of 10 for binary galaxies, and several hundred for most clusters of galaxies. So far, the best-understood system is probably the twin quasar 0957 + 561, discovered by Walsh, Carswell, and Weymann. Through the optical work of Young *et al.*, the VLA observations of Greenfield *et al.*, and the VLBI work of Porcas *et al.*, and Gorenstein *et al.*, it is clear that the lensing material associated with the observed foreground cluster must be composed mostly of dark matter distributed rather differently from the visible matter.

The evidence for dark matter is so strong that it must be accepted. The distribution and nature of the dark matter, however, is still far from clear, and study of this interesting and widespread phenomenon is obviously indicated. A number of promising new methods can be employed, and we are exploring three approaches: the study of the gravitational lensing phenomenon, the measurement of the dynamics of interacting pairs of galaxies, and the study of quasar-galaxy pairs.

The aim is to improve, in a comprehensive way, our knowledge of the distribution of matter in galaxies and clusters of galaxies.

# 13.2 Jovian Decametric Radiation

*David H. Staelin, Philip W. Rosenkranz, Peter M. Garnavich*

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. "Arcs" in the frequency-time domain have been associated with radio emission near the local electron-cyclotron frequency with a hollow conical emission pattern. Theory suggests that such conical emission might be produced by magnetospheric currents generated by the satellite Io as it traverses the magnetospheric fields. These currents, on the order of $10^6$ amps, are believed to propagate in an Alfvén wave that is reflected repeatedly between the northern and southern Jovian ionospheres. These currents traveling along the magnetospheric field lines should be spaced in Jovian longitude by an amount that depends upon the Jovian magnetic field strength and the plasma density in the magnetosphere, which is dominated by the plasma located in the "plasma torus" produced near the orbit of Io by volcanic activity. It would be natural to associate the spacing of the Jovian arcs with the spacing between the separate reflections of the Io-generated currents.

Examination of ~ 200 arcs and ~ 200 gaps between arcs observed by Voyager 1 and 2 did not reveal the expected correlation between arc gaps and longitude; in general the arc spacings were often half of the values expected and were only weakly dependent on longitude. This model assumed a constant cone angle. If, however, there is a simple relation between arc vertex frequency and longitude, the arc cone angle can be deduced; the half-cone angles deduced in this fashion varied between ~ 40° and 90°. Thus, if the Alfvén-wave model is correct, the cone angle must vary considerably from one current stream to the next, and may even have multiple values within a single current stream. This could also explain the close spacings observed for S-burst arcs, which may arise from similar currents.

Analysis of Jovian decametric data has been based primarily on 48-sec averages of 6-sec spectra which have been displayed with limited dynamic range, thus obscuring much structure. Software to display this data with 6-sec resolution and with an easily adjusted dynamic range has been developed. New phenomena and better images of old phenomena will be sought during 1984.

## References

1. P.M. Garnavich, "Jovian Decametric Radiation: A Test of the Multiple-Reflection Alfvén Wave Model," S.M. Thesis, Department of Physics, M.I.T., June 1983.

# 13.3 Long-Baseline Astrometric Interferometer

*Michael Shao, David H. Staelin, Mark Colavita, D. Cosmo Papa*

During 1983 the Mark II optical astrometric interferometer was successfully used at Mount Wilson Observatory in California to track stellar fringes in two colors for the first time. This instrument has two 10-inch siderostat mirrors 3.4 meters apart in a north-south direction. Within the ~ 2-inch aperture the positions of red and blue fringes are independently estimated every ~ 2-10 ms, thus permitting the state of the atmosphere to be measured and compensated over time intervals sufficiently short that the atmosphere can be considered "frozen".

One typical experiment (August 31) tracked Alpha Lyra for 80 seconds with ~ 0.07 arc sec rms deviation from mean position (1-sec position measurements) in the red band, and with ~ 0.02 arc sec rms deviations when both the red and blue fringe positions were considered. The formal error for 80 such 1-sec measurements, if their errors are uncorrelated, is ~ 0.002 arc sec, much better than ever before achieved for so brief a measurement.

The primary purpose of the Mark II experiment is demonstration and evaluation of the two-color technique for obtaining relative astrometric positions accurate to ~ $10^{-3}$ arc sec rms for stellar separations <~ 1°. Experiments to demonstrate wide angle ($\gtrsim$ 10 °) and absolute astrometry are also being planned for the Mark II instrument in collaboration with the Naval Research Laboratory. Future versions of the interferometer are expected to achieve $10^{-4}$ arc sec relative position accuracy over 1-2° stellar separation, which would be adequate to detect a Jupiter near a one-solar-mass star at a distance of several parsecs, with a signal-to-noise ratio of ~ 10.

# 13.4 Tiros-N Satellite Microwave Sounder

*Philip W. Rosenkranz, David H. Staelin, Krishna S. Nathan*

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 a four-channel passive microwave spectrometer (MSU) for the purpose of mapping the three-dimensional temperature field of the atmosphere at six- or twelve-hour intervals. The purpose of this research program is continued improvement in the utilization of the passive microwave data produced by these NOAA satellites.

A two-dimensional spatial filter, optimum in the minimum-square-error sense, was used to retrieve

atmospheric temperature profiles from operational MSU observations. The apparent reduction in retrieved error due to use of two-dimensional techniques (rather than one-dimensional) is greatest in the troposphere and tropopause, and in regions where the verification data sets are more reliable. A large part of the improvement is due to the reduction of the short spatial wavelength errors. The two-dimensional method also significantly surpassed the traditional one-dimensional retrieval method over a severe storm front that contained layers of air with substantially different lapse rates.

During this year a preliminary design was formulated for the operational sounding data retrieval system for the next generation operational low-earth orbit meteorological satellites. In particular, efficient methods were formulated for incorporating both nonlinear physical effects and *a priori* statistics in the retrieval of atmospheric temperature and water vapor profiles from microwave and infrared images obtained from a proposed 20-channel microwave spectrometer and a comparable infrared system.

### References

1. K.S. Nathan, "Application of a Multi-Dimensional Filter to Temperature Profile Retrieval," S.M. Thesis, Department of Electrical Engineering and Computer Science, M.I.T., May 1983.

## 13.5 Improved Microwave Retrieval Techniques

*Philip W. Rosenkranz, David H. Staelin*

This program is directed toward development of improved techniques for retrieval of atmospheric temperature, wind, and humidity fields from passive microwave measurements of the earth, as obtained from satellites. It was concluded in the spring of 1983.

The major effort was continuation of the study of the growth of initialization errors (due to remote sensing errors) in numerical weather prediction models. The initial experiments were extended to a more complete study of the consequences of using different sets of basis functions for describing the altitude distribution of errors. A transition was made from the numerical prediction model on the Cray computer at the National Center for Atmospheric Research to the similar but slightly smaller and more economic model at the University of Wisconsin. This work is continuing under NASA sponsorship, as described below.

## 13.6 High-Spatial-Resolution Passive Microwave Sounding Systems

*Philip W. Rosenkranz, David H. Staelin, Alain C. Briançon, John W. Barrett*

The theoretical portion of this new research effort will explore methods for obtaining high–spatial–resolution passive microwave remote sensing atmospheric data and for obtaining the maximum benefit from such data in numerical weather prediction systems. In the initial months this effort has focused on 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.

Theoretical analysis of aperture synthesis methods suggests that a two–receiver 118–GHz interferometer employing two 35–cm apertures at spacings of zero to three meters, and at all rotation angles, can yield ~ 30–km spatial resolution and ~ 0.3 K rms sensitivity over 640,000 $km^2$ in a few minutes' time. Thus this technique appears quite promising for use in geosynchronous meteorological satellites.

The experimental portion of this effort involves development of a 118–GHz spectrometer for imaging frontal systems from aircraft. A basic system concept has been formulated and procurement of critical components will begin shortly in order to be ready for initial flights in 1985.

# 13.7 Scanning Multi-Channel Microwave Radiometer (SMMR)

*Philip W. Rosenkranz, David H. Staelin, Xi Ru Xu*

On October 24, 1978, the Nimbus–7 satellite was launched into polar orbit carrying the Scanning Multi–Channel Microwave Radiometer (SMMR) and other instruments. SMMR separately measures vertically and horizontally polarized terrestrial thermal radiation at wavelengths of 0.81, 1.4, 1.7, 2.8, and 4.6 cm. The mechanically scanned antenna maps all 10 channels completely over a 780–km wide swath beneath the spacecraft with a ground resolution ranging from ~ 30 km to ~ 150 km, depending on wavelength. Two efforts were concluded during 1983, those concerned with estimating water vapor abundances over arctic sea ice and firn, and snow accumulation rates over Antarctica and Greenland.

# 13.8 Video-Bandwidth Compression Techniques

*David H. Staelin, Donald E. Troxel, Alan S. Willsky, Ali D.S. Ali, Jeffrey G. Bernstein, Biswa Ghosh, Brian L. Hinman, Katherine H. Lambert, Henrique S. Malvar, Joan M. Sulecki*

The monochrome video recording and display system has become fully operational and has been used extensively to record images and to test coding techniques. The video format most frequently

used is 128 x 120 pels at 15 frames per second (fps), where the same frame–store memory contents are displayed with interlace at 60 fps in a 256 x 240–pel bilinearly interpolated format. Images of 256 x 240 pels at 7.5 fps, bilinearly interpolated to 512 x 480 pels, can also be studied at 4 bits per pel, as can 128 x 50 or 64 x 100–pel images at 30 fps and 8 bits per pel. Other combinations are also operational, as limited by the peak data transfer rate to and from the disk memory. Up to 90–sec continuous sequences can be studied.

The most successful video coding technique tested to date is a form of adaptive transform coding using selective replenishment and the short–space Fourier transform (SSFT). The SSFT was developed by Jeffrey Bernstein and Brian Hinman, and is similar to the mutli–dimensional short–time Fourier transform. The SSFT–coded images exhibit no "blocking effects" of the type produced when discrete cosine transforms are employed in a block format. Fully recognizable 128 x 120–pel head–and–shoulders images with considerable head motion have been coded at ~ 56 kbps rates, and much improvement appears to be possible. Experiments were also performed using adaptive two–band (high's and low's) coding techniques with selective replenishment. Morphological coding methods, wherein the image is decomposed into strokes resembling the brush strokes of an artist, are also being studied. These methods suffer from noise introduced by inconsistent resolution of ambiguities, but do suggest a soft upper bound to compression ratios for certain classes of image compression techniques.

# 13.9 Resolution–Preserving Interpolation of Video Frames

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As part of the Advanced Television Research Program the use of resolution–preserving interpolation techniques to reconstruct missing frames in a frame sequence is being studied. The facility being used is the same as described above. A second Nova–4 computer and 130–Mbyte disk have also been added to the system. The initial research effort has three aspects, the study of 1) optimum interpolation techniques for subsampled signals in the presence of sampling noise and observer characteristics, 2) motion estimation and motion–compensated interpolation of video sequences, and 3) applications of the short–space Fourier transform to video signal processing. Theoretical work has begun on all three problems, and initial techniques for motion–compensated interpolation have been successfully implemented. A moving head–and–shoulders sequence has been sampled at 7.5 fps, and the missing frames have been reconstructed with sufficient accuracy so as to be nearly indistinguishable from the original sequence. Comparison with reconstructions using only dissolving techniques (i.e., linear combinations of adjacent frames) show a marked superiority for resolution–preserving techniques. Reconstruction of eight intermediate frames between frame pairs yields a slow motion sequence where interpolation artifacts are most visible. In this test slow

motion sequence the only artifacts evident were a slight periodicity at 7.5 Hz in the image blur, and a small apparent discontinuity in velocity vector direction at one point in the sequence.

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