

## ***B. Scientific Staff Research Activities***

### **Cosmology, Large Scale Structure, Galaxy Formation, and Gravitational Lensing**

Brian Mason, in collaboration Anthony Readhead's group at Caltech, has made the best measurements to date of radio-wavelength arcminute-scale anisotropy in the cosmic microwave background (CMB) using the Cosmic Background Imager (CBI). These measurements show, at the 3-sigma level, indications of signal in excess of intrinsic CMB anisotropy on the smallest angular scales, possibly caused a secondary Sunyaev-Zel'dovich (SZ) anisotropy. Recent results of a 30 GHz survey of discrete sources with the GBT have confirmed that traditional mJy-level radio galaxies contribute little to the observed high-ell excess. Further GBT data will be brought to bear on the contribution of fainter populations of sources, in particular of "starbursting" galaxies at faint flux densities. In collaboration with E. Waldram and collaborators at Cambridge and Oxford universities, further radio data will be brought to bear on the problem as well.

Mason, in collaboration with T. Robishaw (Berkeley) and D. Finkbeiner (Harvard), has developed the technique of sensitive broadband continuum polarimetry for the GBT. This technique yields nearly theoretical noise performance for broadband measurements of Stokes Q and U, and it was used to set limits on polarized emission from spinning dust in the dark cloud LDN1622 at 8 GHz. The technique will be applied at higher frequencies to LDN1622 and other Galactic sources, as well as to extragalactic discrete sources, yielding vitally important information for future CMB polarization experiments that must reach NanoKelvin sensitivities.

With a broad variety of collaborators, Mason is making first use of the GBT at 90 GHz for a variety of early science projects with the MUSTANG bolometer array. Aims of these studies range from constraining grain size distributions in star forming regions to better determining the long-wavelength SEDs of high redshift galaxies.

In collaboration with K. Spekkens and J. Aguirre, Mason is using continuum data from the GBT to detect or set limits on the self-interaction cross section of dark matter in nearby Dwarf Galaxies.

Dan Marrone, with J. Carlstrom (UChicago), M. Joy (NASA), M. Bonamente (UAH), G. Smith (Birmingham) and others, is studying galaxy clusters through their imprint on the Cosmic Microwave Background (the Sunyaev-Zel'dovich Effect, SZE). The SZE is a unique tool for studying structure formation in the universe, but many questions about the relationship between the SZ signal and cluster properties remain unanswered. In particular, the expected low-scatter scaling between the SZ observable and cluster mass, which is critical to using these objects for dark energy studies, has not been verified observationally. Through SZE observations with the Sunyaev-Zel'dovich Array (SZA) and supporting information from gravitational lensing and X-ray measurements, they are performing the first comparison of gravitational masses and the SZ signal and SZ-derived hydrostatic mass. Over the next year, the SZ signal will be cross-calibrated against a variety of observables as part of the Local Cluster Substructure Survey. Marrone will also work to integrate the SZA into CARMA in late 2008, which will increase the sensitivity and angular dynamic range for imaging of the SZE. Finally, results from the SZA cluster survey led by S. Muchovej (Columbia) and a sensitive measurement of arcminute-scale CMB anisotropy (M. Sharp, UChicago) are being compiled for release this fall.

Steve Myers and collaborators are using the VLBA and HSA to find and/or place limits on the existence of so-called “core images” in gravitational lens systems, which is a sensitive test of the gravitational potential in the center of the lensing galaxy. This work will place important limits on the radial profiles and relative masses of dark matter and gas. These are part of a program of follow-up observations of candidate gravitational lens systems discovered in the VLA Cosmic Lens All-Sky Survey (CLASS).

Myers, Brian Mason, and Marian Pospieszalski are working with the Cosmic Background Imager (CBI) collaboration to analyze the observations of Cosmic Microwave Background radiation (CMBR) and the Sunyaev-Zel'dovich Effect (SZE) in clusters of galaxies taken with the CBI from the ALMA site in Atacama, Chile. CBI observations of the SZE will be combined with those taken with other instruments such as X-ray observations by Chandra and XMM, weak lensing in the optical/infrared, and radio observations using VLA and ATCA, in order to constrain cosmological parameters and the astrophysics of the intra-cluster medium.

Steve Myers is working with J. Sievers, Ue-Li Pen, and Tzu-Ching Chang (CITA) on 150 MHz observations of the redshifted 21 cm hydrogen line during the epoch of reionization using the GMRT.

Jim Braatz will continue his work on the Megamaser Cosmology Project (MCP), which aims to make a precise determination of the Hubble Constant by measuring geometric distances to galaxies using the maser distance technique pioneered on NGC 4258. Collaborators include Cheng-Yu Kuo (UVA), Mark Reid, Lincoln Greenhill, Avanti Tilak (CfA), Fred Lo, Jim Condon (NRAO), Christian Henkel (MPIfR), Lei Hao (Cornell) and Ingyin Zaw (NYU). The MCP involves first identifying maser disk galaxies through single-dish surveys, then mapping the detected maser disks with sensitive VLBI observations, measuring centripetal accelerations using GBT monitoring of the systemic maser lines, and modeling the disk to determine the galaxy's distance. The project continues in all phases. GBT surveys concentrate on nearby narrow-line AGNs identified by the SDSS, and continue to be productive: 28 extragalactic masers have been discovered by the MCP so far, several of them being candidates for a distance measurement. The VLBI observations are sensitivity-limited and require multiple tracks on each source. The MCP team is making multi-track maps of the high-priority targets NGC 6323 and UGC 3789 to refine the distance measurements to each galaxy. The team has mapped the maser in the high-priority galaxy Mrk 1419 for the first time, and is currently working on multi-track observations to attain the sensitivity required to measure a robust maser distance to that one as well. More sophisticated 3-D modeling of the warped maser disk will be developed to refine the maser distance determinations.

As a complement to measurements of CMB anisotropy, a precise ( $< 3\%$  rms) measurement of the Hubble Constant would provide a valuable constraint on several key cosmological parameters, including the equation of state of Dark Energy, the density parameter for matter, and the flatness of the universe. Jim Braatz, along with collaborators Lincoln Greenhill and Mark Reid (CfA), Jim Condon and Fred Lo, Christian Henkel (MPIfR), and Lei Hao (Cornell), will continue work on the Megamaser Cosmology Project (MCP), which has the challenging goal of measuring the Hubble constant by finding geometric distances to about 10 galaxies, measured to about 10% each. The distances are measured by making VLBI and GBT observations of water-maser emission from pc-scale accretion disks in the AGN using the technique pioneered on NGC 4258. The collaborators expect considerable progress in the coming year. They have obtained a distance to UGC 3789, the first result obtained with this “geometric” technique on a galaxy in the Hubble flow. Maser disks in Mrk 1419 and NGC 6323 were mapped with unprecedented fidelity, also potentially leading to distance determinations. Surveys for new maser disk sources will continue with the GBT. Already the MCP has yielded 18 new detections, pushing the total number of known extragalactic water masers over 100. Of these 100, about five are strong candidates for distance

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measurements using the maser-disk technique. More detections are needed. The 2008–2009 winter observing season will see the more GBT time devoted to surveys as part of the accepted NRAO large proposal. Once maser-disk galaxies are identified, their maser emission must be monitored with the GBT and mapped with the High Sensitivity Array.

The VLA will be used to probe the volume surrounding isolated galaxies searching for low-mass counterparts through their HI emission. These counterparts are predicted by current models of galaxy formation and of the formation of clusters of galaxies and large-scale structure.

The VLA will be used for a deep survey of low frequency (320 MHz) emission from the “Mitchell-Condon” field, a wide, largely blank field previously surveyed at 1.4 GHz. Improved sensitivity follows from developments in imaging that come from novel ways to account and correct for the effects of the ionosphere. The goal is to find objects with abnormal spectral indices that should correspond to unusual objects at moderately high redshifts. A wealth of optical material is in hand for this field.

Together with Ed Fomalont and former Jansky Fellow, Neal Miller, and colleagues from ESO, K. I. Kellermann is using the VLA, Chandra, and the VLT as well as data from Spitzer to study the radio, X-ray optical, and FIR emission from galaxies over a wide range of redshift with the aim of extending and understanding the cosmic history of star-formation and black hole formation and the relation between the two or so-called AGN “feed-back.” We have published the first 20 and 6 cm radio and optical studies from the pointed Chandra and VLA observations of the Chandra Deep Field South (CDFS) as well as the multiple pointing VLA observations led by Miller of the Extended CDFS (ECDFS). A somewhat surprising result was the apparent large AGN content of the sub-milliJansky population. They will refine these results by a more detailed investigation of the CDFS X-ray and optical properties, of catalogued radio sources, including new spectroscopic measurements, to fill in the missing values from the early complete sample of redshifts. Over the next year, work will focus on the new 6 cm VLA observations which are being analyzed in collaboration with colleagues from Arizona State University, Miller's second release of the ECDFS catalogue, the recently released new 2 Msec Chandra observations, and the extensive FIR observations obtained under the FIDEL Spitzer program led by Mark Dickenson. An early specific goal will be to investigate the FIR-radio correlation out to cosmologically significant redshift. When the 4 Gbit data rate is implemented, they may try a high sensitivity Effelsberg-GBT VLBI observation which will unambiguously distinguish between AGN and star formation even for the weakest radio sources.

Distant sub-millimeter galaxies are believed to be progenitors of massive spheroidals observed in the local universe. Whether their clustering properties are similar to those of spheroidals in galaxy clusters is a question that will be address by large scale millimeter mapping with future bolometer cameras such as SCUBA-2. However, the large amounts of multi-wavelength data provided by the COSMOS project permit to address part of this issue by studying the environment of sub-millimeter galaxies. In collaboration with F. Bertoldi (Bonn), C. Carilli (NRAO), E. Schinnerer (MPIA), H. McKracken (Paris) and M. Salvato (Caltech), Manuel Aravena will study of infrared selected galaxies in the surroundings of sub-millimeter galaxies. Current observations provide the first real evidence of clustering around sub-millimeter galaxies. The extension of this study to other deep fields such as CDF-S will allow to test these results in statistically significant galaxy samples.

Aravena has started a project to study the molecular gas, structure and dynamics of a distant millimeter selected galaxy (J100038+020822) in the COSMOS field. The X-ray, optical and infrared properties of this object strongly suggest that it constitutes a transitional case between a starburst to a QSO. Using the

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IRAM 30 m telescope, four CO emission lines have already been detected: J=2-1, 4-3, 5-4 and 6-5. Aravena and Carilli have started a program to observe the CO 1-0 molecular line using high-resolution imaging with the VLA, in order to reveal the structure and possible interaction features in this system. This will also provide insights into molecular gas physical conditions in the central kiloparsec of the galaxy.

In collaboration with M. Albrecht (Bonn) and F. Bertoldi (Bonn), Aravena will continue the study of atomic and molecular gas in nearby galaxies using the NANTEN-2 and APEX telescopes in Chile. Aravena and collaborators have started a program to map atomic carbon CI 1-0, CI 2-1, and high order CO lines, J=4-3, 7-6, in the centers of nearby galaxies. These observations will help to reveal the importance of X-ray heating as a function of environment in star forming regions and will provide a measure of the gas temperatures and masses, independently from CO. Furthermore, the study of the gas properties in local starburst galaxies via neutral or ionized atomic carbon emission lines supply templates to the study of galaxies in the very early universe, being very important with the coming of ALMA.

Veronica Strazzullo and Maurilio Pannella will continue to work with Frazer Owen and collaborators on the deep SWIRE Lockman Hole field. Photometric redshifts now in hand will provide crucial information for the analysis of the radio selected sample, as well as for several interesting studies of the non-radio emitters, including stacking of radio undetected galaxies. The extended multiwavelength catalog now completed will allow detailed characterization of galaxy samples by stellar masses, star formation and stellar populations' properties.

Strazzullo will continue to work on high redshift galaxy clusters with particular focus on the massive X-ray luminous cluster XMMU J2235-2557 at redshift 1.39. New high resolution NIR data are being analyzed which, in combination with ACS optical data, will allow the most detailed study of the red sequence cluster galaxy population at this redshift. Making use of the whole multiwavelength dataset (U band to IRAC 4.5 $\mu$ ) plus VLT spectroscopy, stellar populations of the cluster members will be studied. The cluster galaxy luminosity function in optical and NIR passbands will also be derived. Collaborators include P. Rosati, R. Gobat and C. Lidman (ESO), M. Nonino (INAF-Trieste), A. Rettura (JHU), N. Menci (INAF-Roma).

Pannella will continue to work on the morphological evolution of massive galaxies in collaboration with the MPE Extragalactic group lead by Ralf Bender. The new coming high angular resolution NIR imager on board the HST will push morphological studies up to redshift 2. This will disclose unprecedented information on the dynamical assembly time scales of the giant elliptical galaxies populating the local Universe.

Pannella will also continue work on the Deep Radio COSMOS Survey, in collaboration with Chris Carilli and the whole COSMOS legacy. The Stacking analysis of the galaxy population up to redshift 4, by allowing to reach ALMA sensitivities (rms  $\sim$  0.2 micro Jy), will give unique insights in the radio micro Jansky population as a function of galaxy stellar mass and stellar population properties, i.e., AGN contribution. Moreover the availability of ACS/HST imaging will characterize the radio detected milli Jansky population as a function of structural parameters.

Frazer Owen is working on a variety of studies of the SWIRE deep field and the GOODS-N in order to understand the connection of AGN activity and star-formation to galaxy evolution. Part of this work involves assembling the basic information from a variety of wavelengths on these fields. The more exciting goal is to combine the datasets to derive physical insight into the processes involved in galaxy

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evolution. This work is being done with Pannella, Strazzullo, Wang, Morrison (UH/CHFT), Polletta (Milan) Baker (Rutgers), Shupe (Herschel), Wilkes (CfA), Kilgard (Wesleyan), Omont (IAP), Oliver (Sussex), Ivison (ROE), Biggs (ROE), and Marvil (NMT). A key component of this work is increasing our knowledge of the distances to the faint objects in the deep fields using photometric redshifts which has primarily involved work with first four astronomers in the list. Besides studies of the individual objects, much of the analysis relies on using the redshifts to form stacks of similar objects from images at other wavelengths too shallow to detect objects individually.

Stacks of deep 24, 70, and 160 micron data from Spitzer are being combined with deep VLA 20 cm data in order to study the evolution of the radio-FIR relation with redshift and radio luminosity. New, very deep Herschel imaging of the SWIRE field in five bands between 100 and 500 microns is also expected to be available during the next year which will improve our ability to pin down the FIR component. The SWIRE and GOODS surveys are also being studied to learn how the radio brightness distribution relates to the optical and NIR light from stars. These studies use both ground-based and HST optical/NIR data combined with VLA radio images. These studies will be used to separate galaxies with significant AGN output in the form of mechanical energy from those with those whose radio emission is driven by star-formation. Chandra and XMM X-ray images (both stacks and individual detections) will be used to study relation-dominated AGN population and how closely these objects are related to radio star-forming and mechanical-energy-driven samples.

Ron Maddalena, with Paul Vanden Bout, Jeff Wagg, C. Figura (Wartburg College), and the late Phil Solomon (SUNY at Stony Brook), are using the GBT to search for low-excitation CO emission in the J=1-0 line from galaxies at high redshifts ( $z > 2$ ). By comparing the emission from the J=1-0 line to that in the J=3-2 or 4-3 lines, one can determine if the CO is optically thick and whether these galaxies contain large amounts of cold molecular gas.

R.C. Bignell in collaboration with S. Curran (UNSW) carried out analysis of observations using the GBT to search for HI and OH absorption in red shifted galaxies and quasars. Observations of both blind and targeted searches were completed in the last fiscal year. HI absorption was discovered in the  $z=0.96$  early type lensing galaxy toward MG J0414+0534. This result is interesting in that (a) the HI absorption is split into two components consistent with the two strongest lensing components and (b) there is no strong OH absorption (unlike the other three known lenses) supporting the suggestion that the under abundance of molecular gas and that the extinction occurs primarily in the quasar host galaxy ( $z=2.64$ ). Observations will be undertaken next year of a more sensitive search for OH absorption in the MG J0414+0534 and to detect HI absorption in three other DLAs. The processing of the observational data for the remaining targeted and blind HI absorption searches (observations completed in this last fiscal year) will also be undertaken during the next year.

Maddalena, Vanden Bout, Carilli, and the late Solomon are also using the GBT to search for HCN emission from PSS K2322, a high-redshift FIR-luminous galaxy. Since HCN directly traces dense molecular gas from star-forming regions, these observations may provide evidence that star formation is a major source of the FIR luminosity.

Eduardo Hardy is part of the MUSYC collaboration to perform ASTE-AzTEC imaging at 1.1 mm of 1600 arcmin<sup>2</sup> in the Extended Chandra Deep Field-South (E-CDFS) and the Extended Hubble Deep Field South (E-HDFS) to rms noise level of 2.1 mJy, and 2.6 mJy at 1.1 mm, respectively. This project initiated in 2007 has received additional observing time at ASTE for 2008.

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Aaron Evans will continue his study of the star formation and active galactic nuclei (AGN) properties of Luminous Infrared Galaxies (LIRGs: 8-1000 micron infrared luminosity  $> \sim 10^{11}$  solar luminosities) as part of the Great Observatories All-sky LIRGs Survey (GOALS) collaboration (see <http://goals.ipac.caltech.edu/>). The project makes use of the Hubble Space Telescope, the Spitzer Space Telescope, the Chandra Space Observatory, and the Galaxy Evolution Explorer (GALEX) to sample the energetics of these galaxies over much of the electromagnetic spectrum. As part of this work, Evans, who is the PI of the HST ultraviolet and optical survey, will continue to work with graduate student Tatjana Vavilkin (Stony Brook) to analyze the properties of optically-visible star clusters. In addition, Evans is the co-I of a pilot CARMA project to obtain CO(1-0) observations of a subset of the GOALS sample. Evans and the GOALS team will also begin folding in high-resolution VLA continuum data to their multi-wavelength analysis. The radio data trace star formation via supernovae feedback, an important issue in understanding the evolution of such energetic galaxies.

### **Radio Galaxies, Quasars, Active Galaxies, and Gamma-Ray Bursts**

Emmanuel Momjian, in collaboration with K. Knudsen, C. Carilli, and W-H. Wang, will work on 1.4 GHz VLBI continuum imaging of the luminous sub-millimeter galaxy GOODS 850-3 at  $z=1.8$  to resolve its compact radio emission as seen with the VLA+MERLIN. The VLBI observations, which have already been carried out using the High Sensitivity Array (HSA) at its highest recording rate (512 Mbps), will make it possible to conduct a detailed study on the radio continuum emission from this source on scales of 0.02 to 0.2 arcseconds, allowing us to distinguish between AGN and/or starburst components in this galaxy. This work, combined with others obtained at various wavelengths, will provide a better understanding of the evolutionary status of this high- $z$ , strong far-IR emitting object.

Esteban Araya, in collaboration with Y. Pihlstrom (UNM) and G. Taylor (UNM), will be working on high angular resolution (VLBI) observations of HI absorption in a sample of active galactic nuclei (AGN). This work will enable a study of the kinematics and distribution of atomic gas in the vicinities of supermassive black holes. The final goal of the project is to investigate the circumnuclear environment and fueling of AGNs as a function of luminosity type. Particular attention will be given to HI absorption in compact symmetric objects, which are likely to be very young radio galaxies.

Frank Ghigo is collaborating with Y. Kovalev of MPIfR (Bonn) and G. Langston in studying the motions and variability of the jet components in the BL Lac object PKS1413+135.

Rau (NMT/NRAO), Eilek (NMT/NRAO) and Owen will work on determining the radio brightness distribution of the M87 halo as a function of radio frequency with the VLA between 15 and 90 cm. The goal is to study the inflation of the bubble surrounding M87 which is driven by the mechanical energy from the central black hole. The work will require development of new multi-frequency algorithms by Rau which will be useful in the future for EVLA imaging.

Gustaaf van Moorsel, in collaboration with Bjorn Emonts, Jacqueline van Gorkom, Raffaella Morganti, Tom Oosterloo, and Clive Tadhunter, plans to analyze data taken earlier this year of a number of nearby powerful FR-II radio galaxies, which appear to have tidal HI structures, suggesting a recent merger or interaction. These galaxies have fundamentally different HI properties from low-power radio galaxies (compact and FR-I), which do not show any evidence for recent mergers/interactions. The plan is to study in detail the HI structure found in this sample in order to verify whether they are really tidal features related to a recent merger/interaction. If so, this could show a fundamental difference in large-scale HI properties between different types of radio galaxies (low power compact, FR-I and FR-II), which would

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indicate a fundamental difference in formation history and perhaps also the triggering of the radio-loud AGN.

James Miller-Jones is part of an international team, led by M. Turler (Geneva) which has recently had a proposal accepted by ISSI (Bern, Switzerland) for funding to hold two week-long retreats to work on developing and testing (via observations) theoretical models for the high-energy emission of blazars. In the light of the successful launch of the NASA satellite, GLAST, this is timely research, which will lead to a deeper understanding of the physical conditions in relativistic jets.

Together with W. Baan (ASTRON), P. Hofner (NMT), Y. Hagiwara (NAOJ), and Y. Pihlstrom (UNM), Esteban Araya will investigate the distribution of molecular gas in starburst galaxies using formaldehyde as tracer. As a first step of the project, the merger galaxy NGC 520 will be studied in detail. Comparing single dish with interferometric observations, Araya and collaborators will explore what fraction of the high density gas is associated with the nuclear starburst.

The molecular chemistry of nearby starburst galaxies and molecular absorbers at  $z < 1$  will be studied by Juergen Ott in collaboration with Christian Henkel and Axel Weiss (both Max-Planck Institut fuer Radioastronomie), Jim Braatz, Jeff Mangum, and Al Wootten.

To measure the star formation properties of an entire galaxy merger, its main body, and surrounding streamers Juergen Ott will observe the Tadpole in the CO line. This will reveal the possible existence of tidal tail dwarfs and in situ star formation outside of galaxies. Collaborators are John Hibbard, Tom Jarrett (IPAC), and Ute Lisenfeld (U Granada).

Studies of the distribution of CO emission in external galaxies have pointed to the presence of large quantities of dense molecular material in these objects. These studies have yielded a detailed picture of the molecular mass in many external galaxies. But, because the CO emission from external galaxies is dominated by radiative transfer effects, such as high optical depth, it is not a reliable probe of the physical conditions, such as spatial density and kinetic temperature that give rise to star formation in these systems. Emission from less-abundant, higher-dipole moment molecules are better-suited to the task of deriving the spatial density and kinetic temperature of the dense gas in external galaxies. For this reason, emission line studies from molecules such as CS, HCN, HCO<sup>+</sup>, HC<sub>3</sub>N, H<sub>2</sub>CO, and NH<sub>3</sub> have been made toward a variety of mainly nearby galaxies.

The most extensive sets of measurements of the molecular line emission in external galaxies have been done using (mostly) the J=1-0 lines of CO and HCN. Since these ground-state lines of CO and HCN provide only a lower limit to the spatial density in star formation regions ( $n(\text{H}_2) > 10^3 \text{ cm}^{-3}$ ), specific information about the individual physical conditions in these regions requires multi-transition molecular line measurements from high-density tracers. To this end, Jeff Mangum is collaborating on three areas of research designed to take advantage of high-density tracers of the extragalactic star formation process.

**Formaldehyde Densitometry of Starburst Galaxies:** By extending a technique used to derive the spatial density in star formation regions in our own Galaxy, Jeff Mangum, in collaboration with J. Darling (University of Colorado), K. Menten (MPIfR), and C. Henkel (MPIfR) will make the first measurements of the spatial density in starburst galaxies. The relative intensity of the 1(10)-1(11) and 2(11)-2(12) K-doublet transitions of H<sub>2</sub>CO can provide a very accurate densitometer for the active star formation environments found in starburst galaxies. This technique will be applied to samples of i) IR-bright galaxies which exhibit various forms of starburst activity and ii) OH megamaser galaxies using both the

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GBT and VLA. These H<sub>2</sub>CO measurements will also be used to estimate the dense gas mass in our galaxy samples, with the purpose of searching for correlations between the infrared luminosity and the star formation reservoir in these extragalactic environments.

**Cyanoacetylene Densitometry of External Galaxies:** Results from a survey of a sample of galaxies measured using the GBT has shown that Formaldehyde (H<sub>2</sub>CO) line intensity ratios are a reliable and accurate density probe for extragalactic environments. These single-dish K-doublet H<sub>2</sub>CO measurements possess relatively low spatial resolution, which presents a limitation to the interpretation of the spatial density measurements derived. To add a density probe which allows for a higher spatial resolution, and to add to our list of extragalactic density probes, Mangum and Juergen Ott, along with J. Darling (University of Colorado) are investigating the feasibility of using Cyanoacetylene (HC<sub>3</sub>N) as a high-density probe of the star formation environs of luminous (mainly starburst) galaxies. This feasibility study is being evaluated by making GBT measurements of the HC<sub>3</sub>N emission in a small sample of starburst galaxies.

**Kinetic Temperature in Starburst Galaxies:** Results from a survey of a sample of mainly nearby galaxies measured using the GBT has shown that Formaldehyde (H<sub>2</sub>CO) is a reliable and accurate density probe for extragalactic environments. Using the unique sensitivities to kinetic temperature and spatial density afforded by the excitation characteristics of several inversion transitions of NH<sub>3</sub>, Mangum, in collaboration with J. Darling (University of Colorado), K. Menten (MPIfR), and C. Henkel (MPIfR), propose to continue their characterization of the dense gas in galaxies exhibiting starbursts by measuring the kinetic temperature in a sample of galaxies selected for their high infrared luminosity. This extension of our successful galaxy survey will allow us to further study the range of physical conditions which give rise to star formation in some of the most starburst-active galaxies known.

Subcluster A in the Virgo Cluster is centered on the cD galaxy M87 and also contains the elliptical galaxy M84. F. Davies, C. Walker and J. Wrobel are using existing VLBA phase reference data at 43 GHz to search for changes in the relative positions of the cores of M87 and M84. The goal of this student-led project is to obtain a time sequence of relative position measurements with accuracy significantly under 100 microarcseconds using data from 2001-2008. A measurement of, or upper limit for, a linear motion would constrain the relative motion of the two galaxies and has the possibility to provide the first transverse-motion measurement of a galaxy in the heart of the Virgo Cluster. This study will be published in the program period.

Some broad-line active nuclei appear to be energized by black holes with masses below about a million Solar masses. These low-mass active galactic nuclei may be local analogs of the starting conditions, or seeds, for supermassive black holes. Only a few tens of low-mass active galactic nuclei have been reported to date. Each has a 5 GHz-to-optical flux density ratio less than 10 and is thus radio quiet. Three of these active nuclei have 5 GHz detections, all at the submilliJansky level. J. Wrobel, J. Greene, L. Ho, N. Miller, and J. Ulvestad are studying these three, emphasizing the implications of radio structural information on subarcsecond scales; these studies will be published in the program period. Greene and Ho have recently discovered a few hundred low-mass active galactic nuclei and, along with Wrobel, have begun radio studies of this newly-recognized extragalactic population.

Juergen Ott will continue to participate in a large project to map the outer lobes of Centaurus A with the ATCA and Parkes telescopes (PI: Ilana Feain, ATNF). This project will determine the polarization structure of radio lobes at very high spatial resolution, the absorption and magnetic field properties of galaxies along the line of sight, Faraday rotation measures, and the interaction of the radio lobes with the

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surrounding intra-galactic medium. Collaborators are T. Cornwell, R. Ekers, R. Norris, N. McClure-Griffiths (all ATNF), J. Bland-Hawthorne (U Sydney), and M. Haverkorn.

Ken Kellermann works with a group which includes three former Jansky Fellows, scientists in Germany, Holland, and the Netherlands as well as at Caltech and the Goddard SFC, using the VLBA to study the nature of relativistic radio jets in AGN. They use VLBA observations to study the intrinsic velocity, accelerations, and the two dimensional trajectories of the relativistic flow, and compare our data with models and simulations. Emphasis during the next year will be on the analysis of the MOJAVE complete VLBA flux density limited sample to study the statistical properties of jet kinematics, the detailed characteristics of specific sources such as M87, 3C279, NGC 5128, and NGC 1275, as well as with new observations of strong gamma-ray sources detected by GLAST in order to understand and locate the source of gamma-ray activity and the connection to the radio jets.

Robert Reid and collaborator R. Townson (Univ. of Victoria) are studying kpc-scale radio jets that appear to be precessing and, in two cases, are probably “X” jets where the brighter pair of jets is S-shaped. By fitting curves to these jets they can both check if their morphology is consistent with steady precession, and if the geometry is favorable, use special relativity to measure the jet speed kiloparsecs away from the core, since the apparent projected shape of the jet depends on its velocity.

P. Kronberg (Los Alamos) and Reid are also investigating Faraday screens around a powerful radio jet using multifrequency VLA data.

C.M.V. Impellizzeri with A. Roy and C. Henkel (MPIfR) will follow-up single-dish detections of excited OH and CH<sub>3</sub>OH with the EVLA to locate where absorption takes place in those systems and for a better estimate of filling factors and column densities. This will determine the dynamics of the gas in those systems and determine whether it is compatible with a torus-like structure. Further observations at 13.4 GHz and 12.2 GHz with the GBT will be performed to get a more complete picture of the excitation scenario and reveal the physical parameters of the interstellar medium in the innermost galactic regions.

Impellizzeri will continue her work in collaboration with J.P. McKean, A. Roy, C. Henkel, A. Brunthaler (MPIfR), P. Castangia (OAC), and O. Wucknitz (AIfA) to study the properties of a  $z > 2.5$  gravitationally-lensed water maser observed with the global VLBI in continuum and spectral line mode. The continuum observations will better constrain the current lens models in this system, whereas the spectral line observations will map the location of the maser relative to the source continuum flux density. The two observations combined will further lead to a more accurate estimate of its true unlensed luminosity. Also, monitoring with the Arecibo 305 m telescope will be scheduled to study the maser variability on short time-scales. A follow-up project to study more gravitationally lensed, high-redshift quasars is underway, with Effelsberg observations of another ten candidates.

Craig Walker, Chun Ly (UCLA), William Junor (LANL), Phillip Hardee (U Alabama), and NRAO REU student Fred Davies (NMT) are using the VLBA to study the dynamics of the base of the jet in M87. At 43 GHz, the VLBA apparently just resolves the collimation region of the jet and is able to resolve side-to-side structures a short distance farther out. As a result of its relative proximity, high flux density, and high mass black hole, M87 is the best source for the such a study of a jet base on small scales relative to the gravitational radius. A series of 32 observations of M87 were made during 2007 and early 2008 using the VLBA at 43 GHz. For the first 18 observations, the interval was about three weeks. A preliminary movie based on the first 11 epochs demonstrated that motions of around  $2c$  are seen and that the three

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week interval was too long. The final 14 epochs, obtained under a separate proposal, were observed at an interval of five days.

Fortuitously there was a TeV flare detected by VERITAS during the every-five-day sequence of observations described above. At the time, preliminary results indicate that the M87 43 GHz flux density of the core increased and there appears to be a new jet component. So a spin-off project from the above movie project will be to try to understand the relationship between the TeV flare and the activity in the radio near the “core.” The basic nature, and even location, of such flares is not yet understood. At a minimum, the existing data will be studied. But it is likely that new coordinated observations will be proposed. The nature of those observations, and the levels of collaboration with the VERITAS group, will be determined as analysis of the existing data proceeds.

The relatively nearby superluminal source, 3C120, continues to provide interesting constraints on jet physics. This jet is seen at radio, optical, and X-ray frequencies and, in the radio, can be studied over a very wide range of scales. Previous theoretical analysis of helical instabilities in the inner few parsecs of the jet, and an analysis of the implications of X-ray detections of features on kiloparsec scales, have provided constraints on the physical properties of the jet. The current work includes an attempt by Craig Walker and Hardee to determine the structure of the jet in the transition region between parsec and kiloparsec scales using a very long integration at 327 MHz with the VLBA. Also a long term monitoring program by Walker, Hardee and John Benson (NRAO), involving observations at 1.6 GHz with the VLBA every two years, will end in late 2008. Among other things, that project will show what happens when superluminal features encounter stationary or slowly moving features. Activity in the next year will center around final data reduction, interpretation, and publication of the results of the project.

Aaron Evans, in collaboration with Peter Barthel (Groningen), Dave Sanders (Hawaii), Linda Tacconi (MPE, Garching), David Frayer (Herschel Science Center), Dean Hines (Arizona), and Jason Surace (Spitzer Science Center), has an ongoing IRAM 30 m telescope CO(1-0) survey of redshift  $< 0.3$  optically-selected quasi-stellar object (QSO) hosts. These observations are designed to determine whether or not QSO hosts, as a class, reside in molecular gas-rich host galaxies. Such a single-dish survey is a precursor to higher resolution observations with ALMA. Evans and his co-investigators hope to finish the observations and the analysis in the next year.

Bill Cotton will be using the newly commissioned MUSTANG 3 mm bolometer array on the Green Bank Telescope this year to study the balance between particle losses and reacceleration in extended sources in AGNs.

## **Normal Galaxies**

As a new Jansky Fellow, Brian Kent will continue probing nearby galaxies in the local universe with a variety of facilities. He will lead follow-up observations with NRAO facilities for the Arecibo Legacy Fast ALFA survey, a sensitive wide-field extragalactic HI survey. VLA observations of nearby starless gas clouds associated with the Virgo cluster will reveal hints of dynamics and their sizes. The kinematics and dynamics of these gas-rich objects will allow for their placement in the broader context of galaxy evolution and formation in a cluster environment. Collaborators include R. Giovanelli and M.P. Haynes (Cornell), K. Spekkens (Royal Military College of Canada), E. Momjian (NRAO), A. West (UC Berkeley), Juan Cortes (U Chile), and Eduardo Hardy (NRAO). In collaboration with J. Higdon (Georgia Southern) and R. Koopmann (Union College), GBT observations are currently underway to examine the 500 kpc tidal stream around NGC 4532, a galaxy located in the southern periphery of Virgo.

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Brian Kent, in collaboration with R. Giovanelli and M.P. Haynes (Cornell) and D.A. Kornreich (Humboldt State), has analyzed data from both the VLA and Arecibo of HI debris in nearby clusters and our own Local Group. The debris is often found near large disk galaxies. Taking into account the environmental effect on the clouds, including orbital velocities and the ICM density and temperature, simulations utilizing N-body/SPH (smoothed particle hydrodynamics) codes can show the evolution of the clouds after separation from the parent galaxy in various environments. Ram pressure stripping as well as gravitational effects can play important roles in the development of long tidal tails and more complex debris fields.

Dana Balser and W. M. Goss plan to explore if the GBT can be used as a survey instrument to detect optically obscured nuclear star clusters in starburst galaxies using 7 mm radio recombination lines (RRLs). Nuclear star clusters ionize the surrounding gas to produce copious amounts of thermal emission that is not visible at optical or near infrared wavelengths but has been detected in RRL and continuum emission. RRLs are excellent probes of HII regions since a mere detection indicates thermal emission, whereas, continuum emission is more ambiguous. The goal is to merely detect these star clusters that could then be followed up with higher spatial resolution observations.

Emmanuel Momjian will work with S. Borthakur and M. Yun on VLBA L-band spectral-line data sets to investigate the physical properties (e.g. size, mass, covering factor) of HI clouds in disks and halos of nearby galaxies seen in absorption toward background radio-bright quasars. By studying the kinematics of the HI gas, the project will also address whether there is an outflow or whether the HI gas consistent is in accreting and/or rotating material bound to the galaxy.

Momjian will continue working with N. Kanekar, W. Lane, F. Briggs, and J. Chengalur on VLBA observations to measure the compact flux density of a sample of QSOs with HI 21 cm absorption seen in intervening damped Lyman-alpha (DLA) systems on their line of sight. The 330 and 610 MHz VLBA observations will be utilized to measure the covering factor of the absorbers at the redshifted HI-21cm line frequency and thus, to accurately estimate their HI spin temperatures. The study will be used to probe the redshift evolution of the fraction of HI in the cold neutral medium in normal galaxies and provide a test of whether the observed difference in spin temperatures between high redshift DLAs and local spirals is real, stemming from a physical difference in the two classes of systems, or merely an artifact, arising from the extended nature of the quasar radio continuum.

Jim Condon and Qi-feng Yin have constructed a complete sample of several thousand 2MASS galaxies brighter than  $K_s = 12.5$  detected by the 1.4 GHz NVSS. This sample will be used to construct accurate radio luminosity functions for nearby AGN and star-forming galaxies. The luminosity function of starforming galaxies will be used to estimate the local star-formation-rate density and constrain the evolution of star formation at moderate redshifts. Star-formation rates per unit mass will be studied via the ratios of near-infrared to radio flux densities.

The VLA will be used to study the kinematics of several edge-on, superthin galaxies by probing their HI emission with unprecedented resolution and sensitivity. The systems are located in small groups and show clear distortions such as pronounced warping, prolate nuclei and polar rings. However, in spite of the interactions they seem to be able to maintain their very cold disks. These systems are among the most dark-matter-dominated galaxies known.

Juergen Ott continues to PI the large VLA project VLA-ANGST, a volume limited survey to map the HI content of all galaxies out to  $\sim 4$ Mpc (excluding the Local Group). The project has become the focus of

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the PhD projects of Adrienne Stilp (U Washington) and Steven Warren (U Minnesota). The VLA-ANGST survey is a follow-up of the ANGST project to derive the spatially resolved star formation histories with the HST, PI: Julianne Dalcanton (U Washington). The other partners of VLA-ANGST are E. Skillman (U Minnesota), Fabian Walter (Max-Planck-Institut fuer Astronomie), Baerbel Koribalski (Australia Telescope National Facility), and Andrew West (UC Berkeley). Ott is also a member of the Local Volume HI survey (PI: B. Koribalski) which observational period will end soon and Juergen will study the potential similarities of nearby galaxies and Ly alpha absorbers.

Ott will work on the STING survey, a project to map the molecular gas content of nearby IR bright galaxies at the interferometric resolution of the CARMA mm array. This will provide important input to molecular cloud and star formation theories. PI is Alberto Bolatto (U Maryland), and collaborators are Tony Wong (U Illinois), Leo Blitz and Andrew West (both UC Berkeley), Daniela Calzetti (U Mass), Fabian Walter, Adam Leroy, and Frank Bigiel (all Max-Planck Institut fuer Astronomie), Eric Rosolowski (U British Columbia), Stuart Vogel (U Maryland).

Eduardo Hardy, in collaboration with Ricardo Carrera (Padova) and Carme Gallart (IAC), has published a study of the Chemical enrichment history of the Large Magellanic Cloud using Ca II triplet spectroscopy obtained at CTIO. Additional time has been approved at the VLT for an extension of this study to more peripheral regions of the LMC.

### **The Interstellar Medium, Molecular Clouds, Cosmic Masers, Star Formation, and Stellar Evolution**

Jeff Mangum will work in collaboration with H. A. Wootten to analyze a GBT survey of formaldehyde H<sub>2</sub>CO 2(11),1rs (B2(12), 3(12),1rs (B3(13), and 4(13), 1rs(B4(14) emission toward a sample of star-formation regions to exactly identify the high-density locations within star-formation regions, which will give us a gas-density measurement that can be used to compare with the physical properties derived from dust emission and infrared measurements of these regions. Formaldehyde is a proven tracer of the high-density environs of molecular clouds. Wootten and Mangum will also continue their investigation of high excitation thio-formaldehyde lines observed with the CSO with the purpose of developing this line as an alternative tracer of temperature and density.

Wootten, Claussen, Marvel (AAS), and Wilking (UMSL) will continue their work on using water masers to trace the kinematics of gas near young stellar objects. One study published recently, the focus of activity has moved to the IRAS16293-2422 system, where masers apparently probe a region within one AU of the central object. In collaboration with Claussen, Marvel, Wilking, and Sarma (DePaul), they have measured the polarization of a strong water maser in the well-known young stellar object IRAS16293,1x2 (B2422). This method is a direct way of measuring the strength of the magnetic field in the close environs of a Sun-like forming star.

In collaboration with the late B. E. Turner, Alwyn Wootten published results of a search for interstellar CH<sub>2</sub>D<sup>+</sup>, an isotopomer of the symmetric and hence undetectable cornerstone ion of interstellar carbon chemistry, CH<sub>3</sub><sup>+</sup>. New receivers have enabled a deeper search for this molecule, to be carried out at the CSO and IRAM 30 m in collaboration with Lis (CIT), Gerin and Roueff (Obs de Paris).

Wootten, along with Gerin, Roueff, and others will use the GBT to survey the <sup>15</sup>N form of NH<sub>3</sub> in dense cores. Isotopic ratios provide important insight into the origin and history of solar system and interstellar materials as they may be preserved in the solar system during the formation of the solar nebula from a

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dense core. They recently detected 15NH<sub>2</sub>D with the IRAM 30 m and plan to complement our survey of that molecule by comparing the 15N abundance ratio in ammonia, in data to be obtained with the GBT.

Wootten with Brogan, Hunter, Indebetouw, Devine, and Drosback, will research the chemistry and physical properties of a particular Infrared-Dark Cloud using CARMA and the VLA. The cloud they will target in particular appears to be a filamentary series of cores forming massive stars in several places along its spine.

Wootten and Yancy Shirley (U Arizona) will continue a project to characterize the chemistry and kinematics of ions in massive star-forming clouds. They now have a set of images of several dozen clouds in several transitions for each of the bright ions; this data set is currently being analyzed.

Al Wootten will continue his research into the nature of the interstellar shocks that give rise to water masers, using the VLBA to detail proper motions during outbursts discovered during monitoring with the Nobeyama 45 m telescope, the VLA, and the GBT. Active masers identified by monitoring were imaged by the VLBA to detail the characteristics of the maser phenomenon. With M. Claussen, K. Marvel (AAS), and B. Wilking (Missouri, St. Louis), investigations were pursued toward the low-luminosity young binary GV Tau (IRAS 04263+2426) at six epochs over a period of two months during 2004 Jan 23 through March. Observations were interleaved with observations of the phase-reference source J0426+2327 to provide accurate position measurements of the maser features. The maser images detail a single compact structure about 1.2 mas (0.17 AU) in extent. Most authors have theorized that the flow is driven by the more embedded northerly component of the binary, GV Tau B. However, all maser components observed are located within a projected distance of tens of AU of the origin of expansion, the position of GV Tau A. In extremely cold cores surrounding very-low-mass protostars, molecules may freeze out onto grains to the extent that little molecular emission arises from the densest and coldest portion of the core.

In collaboration with H. A. Wootten and B. Matthews (NRC), Antonio Hales has observed, reduced, and analyzed GBT and VLA data of the class 0 source Barnard 1c. Ammonia (1,1) and (2,2) inversion-line maps were used to determine the kinetic temperatures in different regions of the source. The VLA data match the resolution of existing SMA polarimetry data.

Star formation in Infrared Dark Clouds (Katie Devine, Claire Chandler, Crystal Brogan, Ed Churchwell, Remy Indebetouw, and Yancy Shirley): The discovery of thousands of dense clouds opaque at 8 microns by MSX and the Spitzer GLIMPSE survey suggests that infrared dark clouds (IRDCs) may represent the earliest observable phases of massive star formation. These clouds exhibit structure on all spatial scales, and observations using the combination of the GBT and VLA are being used to investigate a sample of IRDCs to probe their morphology, physical properties, chemistry, and kinematics. The transitions of the key molecules CCS and ammonia at 23 GHz being used in this study also have the potential to establish chemical ages for the IRDCs, and will enable direct comparisons with nearby, low-mass, pre-protostellar cores. The GBT, VLA, and SMA are also being used to search for other tracers of active star formation, such as 8 GHz continuum emission, water masers, and molecular outflows, to enable the cloud properties to be correlated with star formation activity.

The Co-ordinated Radio and Infrared Survey for High-Mass Star Formation (CORNISH survey) (Melvin Hoare, Phil Diamond, Ed Churchwell, Bill Botton, Claire Chandler, Stan Kurtz, Debra Shepherd, and the CORNISH team): The CORNISH survey is a 1-arcsecond resolution 5 GHz radio continuum survey of the 110 square degree area of the Galactic plane covered by the northern GLIMPSE SPITZER Legacy

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Programme. The survey will deliver a large, unbiased sample of UCHII regions which will be used to test models of their dynamics, evolution and their feedback role in massive star formation. Radio data will also allow a separation of the radio-loud UCHII regions from their radio-quiet precursors (massive young stellar objects, or MYSOs), which otherwise have very similar IR colors. Previous studies of these early phases of massive star formation have been heavily biased away from dense regions of the plane confused in the IRAS beam, or towards already known complexes. The large (approx. 1000), well-selected sample of MYSOs right across the inner galaxy will allow follow-up observations with ALMA and EVLA to study infall, outflows and stellar winds systematically as functions of mass, age, and environment.

The kinematics of the photoevaporation disk around the massive star in MWC349 (Jesus Martin-Pintado, Claire Chandler, Clemens Thum): They have used the unmatched sensitivity and angular resolution of the VLA-Pie Town link at 22 GHz to measure, for the first time, at the highest angular resolution, the kinematics of the photoevaporation disk around a massive protostar. They have imaged the distribution of the H66-alpha line as a function of radial velocity in MWC349. These images will be used to provide unique information for testing models of ionized winds arising from the photoevaporation of disks.

Crystal Brogan continues her research on massive stars, concentrating on the earliest phases of their evolution and their final death throes as supernova remnants (SNRs). Some of the highlights of this research are described below.

Some of the massive star formation studies underway by Brogan include Submillimeter Array (SMA) studies of the massive protocluster NGC6334I at 345 and 678 GHz in collaboration with T. Hunter (NRAO), R. Indebetouw (Virginia), K. Menten (MPIfR), and H. Beuther (MPIA). The protocluster members show a wide range of properties including two hot cores, a UCHII region and a cold core. New very extended configuration SMA data will be used to unambiguously identify protostellar massive disks within the cluster. With Hunter and Indebetouw, Brogan is also using extended configuration SMA data to study two other massive protostars that span a range of evolutionary state from the very young W33A, to the intermediate age GL2136. The first two sources are particularly interesting since they show a wide range of infrared solid ice features. To better understand the ice evaporation process in young hot disks they are also using the SMA to observe these sources in a wide range of methanol and formaldehyde lines in collaboration with Hunter, M. Gerin (LERMA), E. Roueff (l'Observatoire de Paris), Q. Zhang (CfA), E. Dartois (Institut d'Astrophysique Spatiale) and T. Geballe (Gemini).

Brogan is also involved in several projects to investigate the very earliest phases of massive star formation before the protostar emerges from its natal material as an infrared source. Brogan is supervising in large part the Ph.D. thesis work of Wisconsin student C. Cyganowski in collaboration with Hunter and E. Churchwell (Wisconsin). Cyganowski has identified a sample of ~100 sources in the Spitzer GLIMPSE legacy survey with extended 4.5 micron emission known as EGOs (extended green objects). Based on a small number of previously studied sources, such extended 4.5 micron emission is thought to trace shocked H<sub>2</sub> emission in massive protostellar outflows. Thus, this sample represents a new catalog of candidate high mass protostellar objects. Detailed studies of ~30 EGOs are being pursued including VLA observations of Class I and II methanol masers, and large scale JCMT observations of the molecular gas outflow tracers HCO<sup>+</sup>, and SiO. High angular resolution observations of four of the EGOs using CARMA at 3 mm and SMA at 1.3 mm will also be observed in the coming year. Brogan, together with Indebetouw, Hunter, and A. Wootten (NRAO) will also study one IRDC in great detail in the coming year using a wide range of chemically diagnostic lines observed with the CARMA array at 3 mm.

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A fundamental question in the study of star formation is, “What is the importance of triggering by previous generations of stars versus spontaneous or turbulence mediated collapse?” In the coming year, Brogan will use Spitzer cycle-5 IRS data (in collaboration with Indebetouw, Churchwell, and Cyganowski) to carry out a detailed study of the ionized, photon-dominated region, and neutral zones of four Galactic HII region bubbles with photometric evidence of embedded young stars at their boundaries. This study will allow them to distinguish between the “collect and collapse” and “radiative implosion” models of triggering.

In collaboration with Jeremy Darling (Colorado) and Kelsey Johnson (UVa), Brogan will follow-up on their recent GBT discovery that water masers with luminosities typical of bright Galactic star formation masers may be ubiquitous in star forming galaxies (these Galactic analog water masers are distinct from the megamasers found in the nuclear regions of AGN). A GBT survey is planned of a large sample of nearby star forming galaxies with an unprecedented sensitivity of  $\sim 1$  mJy and a high resolution VLA study of the water masers discovered in the Antennae.

Finally, Brogan continues her research on Galactic SNRs through several low frequency and X-ray projects. In particular, in collaboration (PI) B. Gaensler (Sydney) and a large international team they are engaged in a project called ChIcAGO: Chasing the Identification of ASCA Galactic Objects, which seeks to understand the nature of all of the remaining uncategorized low latitude ( $>100$ ) ASCA X-ray sources, many of which are likely to be unknown SNRs. This project includes multi-wavelength follow up of the ASCA sources in the X-ray (XMM and Chandra), radio (VLA and ATCA), and near infrared (Magellan).

Dana S. Balser, T. M. Bania (Boston University) and R. T. Rood (U of Virginia) will continue their campaign to understand the evolution of helium by using the 8.7 GHz hyperfine transition of  $^3\text{He}^+$ . Recently, Eggleton et al. (2007) used a new 3-D hydrodynamic code to model a low-mass star at the tip of the red giant branch. They discovered an instability that leads to extra-mixing and a concomitant destruction of  $^3\text{He}$ . They claim this is a Raleigh-Taylor instability caused by a molecular weight inversion that is produced by  $^3\text{He}$  burning at the edge of the hydrogen burning shell. This scenario predicts that all stars should experience this instability and destroy the  $^3\text{He}$  produced during main sequence evolution. This is inconsistent with their detections of  $^3\text{He}$  at canonical abundances in the planetary nebulae NGC3242 and J320. These detections, however, were pushing the instrumental limits of the 100m Effelsberg telescope and the VLA, respectively. These collaborators plan to use the GBT and Arecibo telescope to confirm the NGC3242 detection and measure  $^3\text{He}$  in several other candidates. Robust  $^3\text{He}$  PNe detections at canonical abundances will falsify the universality of the Eggleton, et. al., mixing hypothesis.

Balser in collaboration with Bania, L. Anderson (Boston University) and Rood will continue to study Galactic HII regions using radio recombination line (RRL) and continuum observations with the GBT. A survey is underway to detect new HII regions in the Galaxy using 21 cm VGPS continuum and coincident 24 micron MIPS GAL emission. From these data the electron temperatures can be derived. Because metals are the main coolants in the photoionized gas, nebular electron temperature values across the Galactic disk are directly related to the distribution of heavy elements in the Milky Way. Galactic chemical evolution modifies Big Bang abundances by stellar nucleosynthesis that depends on stellar mass, time, and Galactic location. Probing the Galactic metallicity distribution using nebular electron temperatures constrains Galactic chemical evolution models. Chemical abundances in HII regions are typically measured using bright, collisionally excited lines at optical wavelengths which can have large discrepancies, as much as a factor of two in some cases, and where very few good measurements have

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been made in the outer Galaxy. The radio method, although indirect, has several advantages. The optically thin RRLs measure the electron temperature throughout the nebula. Temperature structure does exist and can account for some of the optically determined abundance variations. Moreover, the HII regions can be probed throughout the Galaxy at radio wavelengths to explore, for example, any azimuthal abundance variations.

Emmanuel Momjian will continue working with J. Pandian, Y. Xu, and K. Menten on multi-frequency VLA continuum imaging of massive young stellar objects (MYSOs) associated with a statistically complete sample of 6.7 GHz methanol masers. The study will result in obtaining the spectral energy distribution of the MYSOs in order to distinguish between objects in different stages of evolution, which in turn will help in understanding the link between methanol maser emission and massive star formation.

Momjian will also continue working with J. Pandian, K. Menten and P. Goldsmith in imaging 6.7 GHz methanol masers with MERLIN (and with the EVLA in the near future). The project aims at determining accurate positions with subarcsecond accuracy for the methanol masers discovered in the Arecibo Methanol Galactic Plane Survey, which in turn will determine their infrared counterparts. This work will yield significant insight into the relation between high-mass star formation and the 6.7 GHz methanol maser phenomenon.

Esteban Araya, P. Hofner (NMT), and S. Kurtz (CRyA-UNAM) will continue the study of young massive stellar objects using radio continuum and 44 GHz methanol emission as tracers. The region DR21(OH) will be studied in detail. VLA observations show that methanol maser emission in DR21(OH) originates from a series of bow-shocks in an outflow. High angular resolution continuum observations reveal a double radio continuum source that may be directly associated with the outflow. The double radio source is likely tracing the bow-shocks of an ionized jet. Sub-arcsecond resolution observations of other massive star forming regions have resulted in the detection of a handful of such double radio sources. The occurrence of sequential bow-shocks (as traced by methanol masers) and double radio continuum sources (as traced by free-free emission) may be direct evidence for discrete accretion/outflow events during the formation of massive stars.

Along with P. Hofner (NMT), W. M. Goss (NRAO), S. Kurtz (CRyA-UNAM), H. Linz (MPIfA), and other researchers, Araya will also continue a comprehensive study of formaldehyde masers in the Galaxy. Based on a new single-dish survey, Araya and collaborators will explore whether formaldehyde masers are an exclusive phenomenon associated with massive star formation. Araya, et al., will also investigate the cause of the enigmatic periodic flares in IRAS18566+0408 and the relation between the variability of methanol and formaldehyde masers in the region.

Together with collaborators Jerome Pety (IRAM-Grenoble) and Robert Lucas (ALMA-Chile), Harvey Liszt has embarked on a program of imaging galactic diffuse clouds. The discovery of an unexpectedly rich and ubiquitous diffuse-cloud polyatomic chemistry in millimeter-wave absorption spectra implies formation rates much higher than for thermal chemical reactions, but evidence of shocks and other non-thermal phenomena is lacking in the absorption line profiles and the molecules are too weakly excited to derive the ambient density or temperature. However, the host gas is sometimes identifiable in maps of extinction and CO emission, revealing the local geometry and kinematics around the absorption line of sight. In this way the nature of the physical processes in the host gas may be revealed.

Identification of Star Formation Cores in Molecular Clouds: All current theories which describe the star formation process predict that an essential ingredient is a dense core which seeds the collapse process.

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Many star formation regions have been identified through molecular spectral line and dust continuum measurements, and the physical properties of many of these regions have been derived. Due to the non-selective nature of many of the physical probes used to derive these properties, the exact identification of the highest density regions, and thus the regions which are most likely to form stars, have not been identified.

Formaldehyde (H<sub>2</sub>CO) is a proven tracer of the high density environs of molecular clouds. It is ubiquitous: H<sub>2</sub>CO is associated with 80% of the HII regions surveyed by Downes et. al (1980), and possesses a large number of observationally accessible transitions from centimeter to far-infrared wavelengths. Because H<sub>2</sub>CO is a slightly asymmetric rotor molecule, each rotational energy level is split by this asymmetry into two energy levels. Therefore, the energy levels must be designated by a total angular momentum quantum number, J, the projection of J along the symmetry axis for a limiting prolate symmetric top, K(-1), and the projection of J along the symmetry axis for a limiting oblate symmetric top, K(+1). This splitting leads to two basic types of transitions: the high-frequency  $\Delta J = 1$ ,  $\Delta K(-1) = 0$ ,  $\Delta K(+1) = -1$  “P-branch” transitions and the lower-frequency  $\Delta J = 0$ ,  $\Delta K(-1) = 0$ ,  $\Delta K(+1) = +1$  “Q-branch” transitions, popularly known as the “K-doublet” transitions. The P-branch transitions are only seen in emission in regions where  $n(\text{H}_2) \geq 10^5 \text{ cm}^{-3}$ . The excitation of the K-doublet transitions, though, is not so simple. For  $n(\text{H}_2) \leq 10^5 \text{ cm}^{-3}$ , the lower energy states of the 1(10)-1(11) through 5(14)-5(15) K-doublet transitions become overpopulated due to a collisional selection effect. This overpopulation cools the  $J \leq 5$  K-doublets to excitation temperatures lower than that of the cosmic microwave background, causing them to appear in absorption. For  $n(\text{H}_2) \geq 10^{5.5} \text{ cm}^{-3}$ , this collisional pump is quenched and the  $J \leq 5$  K-doublets are then seen in emission over a wide range of kinetic temperatures and abundances.

In collaboration with A. Wootten (NRAO), Jeff Mangum will continue their long-term project to use the GBT to survey the H<sub>2</sub>CO 2(11)-2(12), 3(12)-3(13), and 4(13)-4(14) emission toward a sample of star formation regions to exactly identify the high density locations within star formation regions, which will give us a gas density measurement which can be used to compare with the physical properties derived from dust emission and infrared measurements of these regions.

Tracing Protostellar Mass During Star Formation with 7 mm and 9 mm Continuum: Two of the more direct observables which constrain protostellar evolutionary theories are the spectral energy distribution (SED) and the spatial intensity distribution of dust continuum emission. Until recently the main tool for determining the evolutionary state of a protostellar core has been measurements of the SED. Unfortunately, the relationship between the SED and the distribution of matter in a protostellar core is not unique. A powerful tool for constraining the distribution of matter in a protostellar core is the measurement of the spatial intensity of long-wavelength (optically-thin) dust continuum emission. During the last decade, instrumentation such as the Submillimeter Common User Bolometer Array (SCUBA) have been developed which greatly enhance our ability to make measurements of the spatial distribution of matter in protostellar cores over spatial scales ( $10^{3.4}$  AU) which can be used to constrain evolutionary theories.

High spatial resolution measurements of the centimeter-wavelength dust continuum emission are key to these evolutionary characterizations, as long-wavelength dust continuum emission has the highest probability of being optically-thin, and therefore a direct measure of the mass in a protostellar core. When combined with dust continuum observations at submillimeter wavelengths, millimeter continuum observations provide a substantial lever-arm to constrain dust opacities. In collaboration with Y. Shirley

(University of Arizona), B. Mason and W. Cotton, Mangum will use the GBT to image protostellar cores at 7 mm and 9 mm.

A Study of Hot Cores Using Vibrational Molecular Excitation: Studies of the physical conditions within “hot core” ( $n(\text{H}_2) \gg 10^6 \text{ cm}^{-3}$ ;  $T_k > 100 \text{ K}$ ) environments can be made using measurements of dust continuum or spectral line emission. Of fundamental importance to these studies are the location and intensity of the source(s) of their internal radiation fields. The high dust extinction in these cores results in reprocessing of stellar radiation to the near- and mid-infrared portions of the spectrum, but also veils the sources from observation owing to high dust optical depth. The source of radiation—often multiple in high mass star formation regions—remains poorly characterized. Fortunately, information on the internal radiation field within hot cores can be obtained through measurement of infrared—pumped radio wavelength rovibrational molecular transitions. Rovibrational emission preferentially identifies strong infrared sources, thus locating embedded nascent stars within hot core regions. Furthermore, the measurement of rovibrational emission signifies the dominance of infrared radiation processes in hot core environments, thus distinguishing between thermal and dynamical (i.e., outflow) processes in these regions. In collaboration with A. Wootten, Mangum will measure the rovibrational transitions of  $\text{HC}_3\text{N}$  toward hot core environments using the GBT, with eventual follow-up using synthesis instruments.

With Farhad Yusef-Zadeh (Northwestern), Jim Braatz is searching for evidence of star formation in the circumnuclear ring that orbits SgrA\* at a distance of 2-7 pc. Using the GBT, these authors are searching for both maser and thermal emission from methanol, water vapor, and SiO. Collisionally excited class I methanol masers, in particular, provide a signature of early-phase massive star formation.

Juergen Ott will continue to work in the MAGMA collaboration to map the molecular content, traced by CO, of the Large and Small Magellanic Clouds with the high resolution of the 22 m Mopra telescope. The goal is to derive the state of the molecular gas in very different environments. PI of the project is Tony Wong (U Illinois) and collaborators are Annie Hughes, who is a PhD student at Swinburne University of Technology co-supervised by Juergen, Erik Muller (U Nagoya), and Jorge Pineda (JPL).

To complement the surveys of the Large Magellanic Cloud across the electromagnetic spectrum, Ott plans to submit an ultra-large XMM-Newton project to map the LMC in X-rays. The main goals are to derive the spatial distribution of the hot gas and the metals as well as to characterize the entire populations of X-ray binaries, supersoft sources and supernova remnants.

Analog to the highly successful IRAS color-color diagram to classify the circumstellar shells of late-type stars, Mark Claussen and Lorant Sjouwerman will continue the work of their summer student Stephanie Capen (Eastern Nazarene), to exploit MSX and GLIMPSE infrared color-color diagrams to define color selected samples that should yield high detection rates when searched for  $\text{H}_2\text{O}$  and SiO masers.

Lorant Sjouwerman collaborates with Vincent Fish (MIT) on excited-state OH emission in ON1. Global VLBI observations, including the GBT and the new C-band receiver on the EVLA, were performed and will be analyzed to reveal the structure of this star forming region, analog to the observations done on W3(OH) by Fish and Sjouwerman.

Robert Reid, in collaboration with T. Landecker and D. Del Rizzo (DRAO), is studying the outer Galaxy’s warm ionized medium using 1420 MHz polarization data from the Canadian Galactic Plane Survey. The galactic plane in linear polarization is filled with complicated structure that is thought to be from Faraday rotation of a comparatively simple synchrotron radiation field. The Faraday rotation can be

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caused by changes in either the free-electron density or magnetic field strength in the ISM, but in most cases the source of the changes is unknown. There are several known circular features, suggesting that at least in these cases they are being, or have recently been, ionized by stars. Reid is refining an algorithm to quickly and unambiguously detect circular features in a complicated and noisy image.

In collaboration with H. A. Wootten and B. Matthews (NRC), Antonio Hales has observed, reduced, and analyzed GBT data of the class 0 source Barnard 1c. Ammonia (1,1) and (2,2) inversion-line maps were used to determine the kinetic temperatures in different regions of the source. Complementary VLA data matching the resolution of existing SMA polarimetry data has been acquired and reduced using CASA. The VLA maps show an ammonia-depleted inner region, as predicted by theoretical models of this deeply embedded protostellar source. Combining of the single dish and VLA data is undergoing.

Robert L. Dickman and collaborators Darek Lis (Caltech), Michael Skrutskie (UVa), and REU summer student Alex Savello (Emory) will continue their work on the archetypical starless Bok Globule CB4. Recently-obtained CSO observations of the cloud in the J=3-2 isotopic lines of CO made at high spatial and velocity resolution appear to confirm that the cloud is globally subsonic. In the upcoming months the new molecular line data will be analyzed to set an upper limit of the velocity field correlation length. The results of that analysis will be combined with a highly flexible radiative transfer model of the cloud that will constrain the lifetime and thermal structure of the globule.

Dickman will also continue his work on developing and carrying out observational tests to falsify MOND and other theories of modified gravity.

Todd Hunter continues his research in star formation with an emphasis on high mass protostars and protoclusters. In collaboration with Brogan, Indebetouw (NRAO/UVa), Menten (MPIfR), and Beuther (MPIA), subarcsecond-resolution 345 GHz Submillimeter Array (SMA) images obtained in 2007 have revealed tentative evidence for a massive protostellar disk in NGC6334I in a variety of high-excitation, optically-thin lines. Further proof requires the highest angular resolution possible with the SMA (0.3"). Such observations are difficult from Mauna Kea, but this project was recently granted observing time. Hunter and Brogan are also studying the neighboring object NGC 6334I(N). By comparing high resolution VLA water maser and methanol maser images with SMA 1.3 mm molecular line and continuum images, they intend to write a definitive description of this massive protocluster. Hunter is also collaborating with Indebetouw, Brogan, and Wootten in a project to use the CARMA millimeter array to image the dark cloud G24.9-0.2 in six molecular lines in the 3 mm band, including deuterated ammonia, methanol, CCS, N<sub>2</sub>H<sup>+</sup> and HCO<sup>+</sup>. Combined with existing VLA ammonia and CCS images at similar angular resolution, these observations should help quantify the variety of evolutionary stages present across the cloud.

Walter Brisken will continue studies of small scale features of the interstellar medium using unique VLBI observations of pulsar scintillation. The ISM toward pulsar B0834+06 has shown to be rich in structure. These observations build on the scintillation arcs methods developed by Stinebring. Walter will be working with J. P. MacQuart and Steven Tingay (Curtin University of Technology), Adam Deller (incoming Jansky Fellow) and Bill Coles & Barney Rickett (UCSD) on this project.

Time has been secured by Hardy and Cortés (U de Chile) with the APEX and ASTE telescopes in Chajnantor, Northern Chile, for a continuation of a key project of mapping southern interacting galaxies. This mapping is being conducted both in the CO(3-2) line, as well as the dust emission at 870 microns with APEXLABOCA for all sample galaxies. H-alpha observations, complementary to the CO and dust

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mapping, are being conducted with the du Pont telescope at Las Campanas, and will be completed in 2008.

Hardy is part of the Arecibo Legacy Fast ALFA Survey. This collaboration has completed a study of a large HI cloud complex in Virgo. This investigation included CO observations conducted with APEX by Hardy and Cortes (U de Chile) that placed an upper limit to the mass in molecular form. Allowing for uncertainties in the value of the X factor, the metallicity of the cloud gas, and the CO(3–2)/CO(1–0) integrated line ratio, they concluded that the gas mass in the largest cloud is unlikely to be dominated by molecular hydrogen.

Bill Cotton will be working on several coordinated projects studying the atmospheres and mass losing regions of Mira stars using the VLBA and IR interferometers will continue. SiO masers, which can be studied using the VLBA, arise between the outer parts of the molecular envelopes, studied by near IR interferometers (IOTA, CHARA) and the dust forming regions, studied by mid IR (ISI, VLTI/MIDI) interferometers. These coordinated observations can help in the understanding of the mass loss mechanisms in these evolved stars which are one of the major contributors to the interstellar medium and which are currently poorly understood.

The discovery of large organic molecules in the coldest regions of the interstellar medium and in the atmospheres of evolved stars has certainly changed the belief that large organic molecules would only have their origins in hot molecular cores. It has forced us to rethink the paradigms of interstellar chemistry. The work of Anthony Remijan has given us a better understanding of how large biomolecules form and if some part of the prebiotic organic chemistry that occurred on the early Earth had its beginnings in interstellar space. He will continue this investigation specifically with the GBT as the large research proposal: GBT 07A-051: GBT Legacy Survey of Prebiotic Molecules, was awarded 625 hours of time over the next 2.5 years. This project was done in collaboration with Mike Hollis (NASA/GSFC), Frank Lovas (NIST) and Phil Jewell (NRAO). In addition, high-resolution interferometric observations of large molecular species have started with CARMA, the ATCA, and the VLA in order to better understand the location, distribution, kinematics and morphology of the small-scale emission from large organic molecules. These projects are done in collaboration with M. Cunningham & P. Jones (University of New South Wales, Australia), H. L. Kuo, Y. Shaw, L. Snyder, D. Friedel (University of Illinois) and D. Meier (NMT).

In order to unite the efforts between laboratory, observational and theoretical work in astrochemistry, Anthony Remijan and his colleagues, Brooks Pate, Kevin Lehmann, Thomas Gallagher and John T. Yates, Jr. (UVa), Lucy Zuirys (UA), Mike McCarthy (CfA), Eric Herbst (OSU), Frank Lovas (NIST) and Phil Jewell (NRAO) have proposed to NSF Chemistry, with comparable contribution from UVa, for the formation of a “Center for Chemistry of the Universe”. The NSF CCI Center for Chemistry of the Universe will establish an interdisciplinary program to understand the chemical processes in the interstellar medium that provide the initial synthesis of molecules in the universe. The Center will bring together researchers with complementary interests in chemistry, astronomy, astrochemistry, and chemical physics to create a Center that will combine the tools of chemistry and astronomy to test chemical hypotheses for molecular formation under the unusual reaction conditions of the interstellar medium. Although we are still in an era where new, single-molecule observations attract broad interest in the chemistry community and challenge the theoretical models for interstellar molecule formation, they propose that a new approach to understanding the chemistry of the universe is at hand. The broad scientific goal of the Center is to effect a change in the research model of interstellar chemistry. For historical reasons, the field is currently driven by astronomical observations and chemists work to develop

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chemical models to fit these results. They propose to bring chemistry to the forefront and use the tools of astronomy combined with state-of-the-art methods in chemical physics to test mechanisms of interstellar reactions. In this research model, the field will move from survey work to the testing of specific chemical hypotheses.

### **The Galactic Center, Pulsars, Novae, Supernovae, X-ray Binaries, and other Radio Stars**

Mioduszewski has a continuing program with J. L. Sokoloski (Columbia U) and M. P. Rupen (NRAO) to study symbiotic stars. Symbiotics are stars systems with close white dwarf companions and experience large outbursts or nova when enough material from the star accretes onto the white dwarf to start thermonuclear burning. All nova models assume that the accretion disk is destroyed in the nova, but high resolution radio images by the above group of RS Oph after its 2006 nova challenge this assumption. This shows that it is extremely important to continue studying these systems with the VLA and VLBA when they go into outburst if the nova mechanism is to be understood.

Mioduszewski, with James Miller-Jones, M. Rupen, V. Dhawan (NRAO), E. Gallo (UCSB) and P. Jonker (SRON) have a collaboration to study V404Cyg, the most luminous quiescent black hole X-ray binary. They have an global VLBI observation to image V404Cyg with the hope of for the first time imaging the jets of a quiescent black hole. This observation is designed to test the model that jets produce the radio emission seen in quiescent state in X-ray binaries. This collaboration also plans to do astrometry on V404Cyg to obtain a model independent distance. This will allow an interpretation of its 3-D space velocity and determine fundamental properties much more accurately than possible with current distance estimates which are uncertain by almost a factor of two.

Dan Marrone is involved in several studies of the polarization and variability of the Galactic supermassive black hole, Sagittarius A\*. With J. Moran, and D. Munoz (SAO), and R. Rao (ASIAA), Marrone is using the Submillimeter Array to pursue a greater understanding of the physics that power the underluminous black hole at the center of the Milky Way. SMA measurements of Faraday rotation in Sgr A\*, stable over several years, have led to a program to improve the precision of these measurements and detect the fluctuations that would indicate the location of the Faraday screen. This effort involves the SMA and ATCA and is a collaboration with Lorant Sjouwerman and J.P Macquart (see below). Joint monitoring of Sgr A\* across many wavelengths has started to reveal the physics of flaring in the black hole, and these campaigns continue in collaboration with F. Yusef-Zadeh (Northwestern), M Morris (UCLA), C.D. Dowell (JPL), F. Baganoff (MIT), and many others.

The Galactic Center continued to be monitored for intraday variability at 86 GHz by Lorant Sjouwerman, J. P. Macquart (Perth), and Kevin Marvel (AAS) and for polarization variability with Dan Marrone and Ron Ekers (ATNF). The intraday variability is important to characterize the supermassive black hole in terms of existing models and has been claimed by other groups. However, calibration of the instrument and the atmosphere is crucial in the reliability of the results. These new observations were set up to include 86 GHz SiO masers in the field of view so that intraday variability of the Galactic Center source Sagittarius A\* will distinguish itself with respect to the simultaneously calibrated constant flux of the masers in the same field of view.

Harvey Liszt continues his program of interpreting the kinematics and vertical structure of molecular gas in the galactic nucleus. Modelling the dynamics of strong galactic bars provides a systematic way of interpreting the complicated welter of kinematic behavior in the nucleus of the Milky Way and the

recognizable circulation patterns in bar flow models provide a means of sequencing the secular evolution and vertical motion of the Galactic Center gas.

James Miller-Jones will apply the shock-in-jet models developed for blazars to multifrequency VLA lightcurves of the highly variable X-ray binary system Cygnus X-3, in order to compare the physical conditions in the jet in different states of the system, from the giant 10-Jy-level flares to the lower-luminosity yet still active state in which the system spends most of its time. The observations will constrain the variability timescale and polarization of the low-level jets, and the modelling aims to ascertain the physical drivers behind the huge range in radio luminosity (over three orders of magnitude) observed in this system.

With S. Migliari (UCSD), F. Shu (UCSD), and M. Cai (Academia Sinica), Miller-Jones will work on WSRT observations of X-ray binary pulsars, neutron star systems with high magnetic fields. While such systems have never previously been detected in the radio band, the upper limits are not at all constraining compared to the level of radio emission expected from their X-ray luminosities. These observations will either provide a detection or a much more stringent upper limit, constraining the effect of the neutron star magnetic field on the mechanism of jet formation, and testing a model for jet production in high magnetic field systems, originally developed for young stars, in the context of neutron star X-ray binaries. VLA observations of further systems have been requested.

Miller-Jones, Rupen, and Dhawan have also applied for VLBA time to test the prevailing paradigms for jet-disk coupling in neutron star systems (with Fomalont and Migliari) and black hole systems (with J. McClintock (CfA) and R. Narayan (CfA)). The former observations will probe neutron star X-ray binaries over a wide range of mass accretion rates, to establish the importance of this parameter in jet formation. For the black holes, a recent phenomenological model for the jet-disk coupling in such systems has been widely accepted, but its predictions as to the evolution of the jet power and morphology have never been directly tested with high-resolution imaging. These observations are crucial for establishing the reliability of the reigning paradigm. A comparison of the jets in black hole and neutron star systems will establish the importance of a deep gravitational well, a stellar surface, and a magnetic field, in jet formation.

Miller-Jones, in collaboration with R. Fender (Southampton), B. Stappers (Manchester), R. Braun (ATNF), A.G. de Bruyn (ASTRON), and other members of a large team, will continue to work on processing low-frequency (140 and 330 MHz) WSRT data sets of the fields surrounding the X-ray binaries Cygnus X-3, GRS 1915+105 and SS 433. These three persistently radio-bright X-ray binaries are ideal candidates to test the low-frequency behavior of X-ray binary systems, providing important input for the development of transient detection pipelines with LOFAR (see Section 8). These observations will also probe the environments of the sources, searching for evidence of the interactions of the microquasar jets with the ISM.

The molecular component of the Galactic Center will be investigated by Juergen Ott in several large projects, a 20-28 GHz survey of the inner 4 degrees (PI: J. Ott), a high resolution, interferometric ammonia map which is used to derive a temperature map of the inner degree between Sgr B2 and Sgr A\* (with ATCA, PI: J. Ott), and a full 3 mm line survey in the 80-115 GHz range with the Mopra telescope (PI: Michael Burton, U of NSW). Other collaborators are Christian Henkel and Axel Weiss (both Max-Planck Institut fuer Radioastronomie). In addition, Juergen will work on interferometric CARMA data to derive the feeding of Sgr A\* black hole from the surrounding molecular gas.

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In collaboration with Ray Protheroe, David Jones (both U South Australia), Roland Crocker (Monash U), and Ron Ekers (ATNF), Juergen Ott will determine the role of cosmic ray secondary electron production toward the massive molecular cloud complexes in the Galactic Center.

Lorant Sjouwerman and Ylva Pihlstrom (UNM/NRAO) continue to monitor the 1720 MHz masers in the Galactic Center. Most of these masers are produced by the interaction of the Sagittarius A\* East supernova remnant and a giant molecular cloud. Furthermore, high-velocity 1720 MHz masers are located in the circumnuclear disk surrounding the nuclear black hole, Sagittarius A\*, and are believed to be of a different nature; they may be generated by shocks from the collisions of individual clumps in the circumnuclear disk.

Mark McKinnon will continue to investigate the intriguing polarization patterns observed in pulsar radio emission. The patterns are formed when pulsar polarization data on the Poincare sphere are projected in two dimensions. The patterns have shapes of dual clusters, bars, bow ties, and annuli. McKinnon has replicated these shapes with a statistical model of pulsar polarization. Additional studies are needed to link the model with physical processes, most likely propagation effects, occurring in the pulsar magnetosphere. Some of the shapes are easily explained by the ubiquitous orthogonal modes of polarization, which are thought to be the natural modes of wave propagation in the magnetosphere. The more complicated shapes may arise from induced scattering or a stochastic version of generalized Faraday rotation. A possible connection between some shapes and the polarization properties of the so-called “core emission” in pulsars will be explored with polarization observations of individual pulses from pulsars with core-dominated radio emission.

Scott Ransom is playing key roles in two major pulsar surveys, each of which comprises tens of international collaborators. The first is the Pulsar-ALFA survey using the Arecibo telescope, while the second is the 350 MHz driftscan survey undertaken by the GBT during its track repairs in the summer of 2007. Ransom's pulsar-search code (called PRESTO) is being used as the core of the main data-processing pipeline for each of these surveys, which have so far uncovered over 50 pulsars, including 5 new millisecond pulsars. With several hundred terabytes of data taken, though, and more on the way, much work still needs to be done.

Along with Jansky Fellow P. Demorest, and several North American collaborators (including R. Jenet at U Texas, Brownsville, I. Stairs at UBC, and A. Lommen and Franklin & Marshall among others) Ransom is working on ultra-high-precision timing with the GBT and Arecibo, with the ultimate goal of directly detecting nHz gravitational waves. The name for this effort, based on a meeting held in Charlottesville last year is NANOGrav. Much work is ongoing to minimize systematics through better analysis techniques and improved instrumentation.

Along with P. Freire (NAIC), I. Stairs (UBC), J. Hessels (ASTRON), and Ransom's UVa student R. Lynch, Ransom is continuing to work on the timing of the more than 70 new globular-cluster pulsars uncovered by their team using Arecibo and the GBT over the past several years. Many of the pulsars have turned out to be interesting, including several eccentric binaries that constrain the neutron-star equation of state, the fastest-rotating neutron star known, and a millisecond pulsar that might contain one or more Mars-mass planets. New globular cluster searches of GBT data are underway and may provide additional interesting systems. Finally, new HST and ground-based adaptive optics observations will be used to search for the companions for some of these pulsars in collaboration with F. Ferraro (Bologna) and his team.

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Ransom is also part of a large international collaboration that is timing almost 200 young pulsars in the radio such that they might be detected in gamma-rays with *GLAST*. Several of the highest priority pulsars are being timed at the GBT under a project headed by F. Camilo of Columbia Univ. These observations are crucial for the success of the *GLAST* mission.

Walter Brisken, Shami Chatterjee (U Sydney), and Miller Goss, in collaboration with others, will aim to complete a large VLBA pulsar astrometry project, culminating in direct distance measurements to 18 pulsars. This represents a significant increase in the number of pulsars with direct distance measurements. The results will have many implications including improved modelling of ionized material in the Galaxy (and hence for improving distances to other pulsars) and more data constraining the velocity distribution of pulsars and hence the energetics of supernovas.

Goss, with collaborators Jun-Hui Zhao (CfA), Mark Morris (UCLA), and Tao An (Shanghai) are using newly acquired VLA data at 1.3 cm to complete a multi-year study of the proper motions of the HII regions near Sgr A\*, all components of Sgr A West. The VLA data has been acquired with the A and B array and the angular resolution is 0.1 by 0.2 arc sec; it is necessary to take account of the time variations of Sgr A\* during each observation. The time span of the data is 1991 to early 2005. Typical values of proper motion (with respect to Sgr A\*) are 2-4 mas/year with errors at the level of 0.2 to 0.4 mas/year. The precision of earlier VLA determinations of the proper motions of the HII gas is improved considerably. From the VLA archive a new H92 alpha radio recombination line cube is being constructed covering the velocity range -400 to +200 km/s. The velocity resolution is 15 km/s. A number of new features are uncovered in this cube made from nine separate observations in the time range 1990 to 2002. A full 3-D velocity fit (to the two components of proper motion and radial velocity) at a number of points is being carried out. Five orbital parameters are being fit to the three ionized streams in Sgr A West. The relative orientations and locations of the streams can be determined, suggesting that the northern and eastern streams are physically interacting in the mini-bar region. In addition, the VLA archive is being used to construct a multi-year series of images at 6 cm, in order to study the proper motions in Sgr A East, the supernova remnant at the Galactic Center.

The VLA has been used by Goss and Cornelia Lang (Iowa) to study the HI line and continuum towards the central 250 pc of the Galactic Center. The CnB and DnC arrays were used with a resolution of 15 arc sec. Five fields (30 arc min each) were observed. The velocity resolution is 2.5 km/s with a velocity coverage of about -150 to +150 km/s. The continuum image has been used to constrain the possible non thermal contribution of the extended structures near Sgr B2 (with Pat Palmer, Chicago); they find no significant non-thermal contribution based on 327 MHz VLA archival data and our new 1.4 GHz continuum image. These collaborators will use the HI data to construct HI absorption data for 40-50 continuum components. A major goal is to determine the nature of the physical association of the atomic, molecular (from comparison with CO data) and the continuum sources. In many instances they expect to be able to determine relative distances along the line of sight. Of especial interest is the possible association of HI with the massive molecular cloud associated with Sgr B2 at longitude 0.7 degrees. The HI is a minor trace species compared to the hydrogen molecule; a detailed study of the HI spectra with existing VLA data of the 6 cm absorption line will be carried out. This data set should provide an archival collection of HI images in the Galactic Center.

## **The Solar System and other Planetary Systems**

Brigette Hesman will continue collaborating with Bryan Butler (VLA) and Mark Hofstadter (JPL) on VLA observations of Uranus and Neptune. This project also involves the development of a new radiative transfer model of Uranus for the EVLA bands in collaboration with K. Devaraj (PhD student; Georgia Tech), M. Hofstadter (JPL), and B. Butler (NRAO). Analysis of past VLA Uranus and Neptune observations, to determine the temporal changes in their atmosphere's and comparison to model results, is expected to dominate Hesman's research time.

Hesman will also continue her studies of Saturn's latitudinal hydrocarbon abundance profiles. In collaboration with Don Jennings (GSFC), Pedro Sada (Universidad de Monterrey), and Gordon Bjoraker (GSFC) observations of acetylene (C<sub>2</sub>H<sub>2</sub>) and ethane (C<sub>2</sub>H<sub>6</sub>), using a high-resolution cryogenic grating spectrometer, are performed at the NASA InfraRed Telescope Facility (IRTF). These observations are combined with Cassini's Composite Infrared Spectrometer (CIRS) observations. As these observations are complimentary to each other they are used along with temperatures derived by CIRS, to determine latitudinal hydrocarbon profiles across Saturn's southern hemisphere. These latitudinal abundance profiles are used as tracers of atmospheric dynamics and to improve seasonal climate models. This is part of a long-standing program to observe changes in the hydrocarbon profiles throughout Saturn's seasons. Data analysis of previous observations will be performed along with proposals being submitted for continued ground-based observations of Saturn at the IRTF.

Jonathan Romney, in collaboration with Ed Fomalont, Vivek Dhawan (NRAO), Dayton Jones, Jim Border, Myles Standish, and Bob Preston (JPL), will continue the precision VLBA astrometry of the Cassini spacecraft currently orbiting Saturn. This ongoing, multi-year project will substantially enhance the accuracy of the Saturnian orbit. Ephemerides of the outer planets are less well known than those of the inner planets, primarily because there have been few opportunities to supplement classical optical observations with modern, high-precision results from Doppler tracking and interferometric angular measurements. These observations, started as a follow-on to the VLBA Spacecraft Navigation Pilot Project, aim to reduce the Saturnian ephemeris uncertainties to 2 km in longitude, 7 km in latitude, and 0.4 km in range, a factor of 2-3 smaller than the current uncertainty for each coordinate.

Hales, in collaboration with M. Barlow (UCL) and J. Drew and Y. Unruh (Imperial College), has conducted an unbiased survey for 8 and 24 micron excesses due to hot and warm circumstellar dust around Galactic main-sequence A-type stars. Results indicate that excesses at these wavelengths are rare (1.2%), in accord with what is expected from steady evolution of collisional grinding in debris disks. The paper presenting the results from this preliminary data was submitted to ApJ. Data are still being collected at the Isaac Newton Telescope in La Palma (approaching survey completion). Early Data Release (EDR) was completed in Spring 2008 (Gonzales-Solares et al. 2008), where photometry for 200 million objects was made available to the community through the Virtual Observatory (VO) network. An extension of the debris disk search is being carried out, which will allow for a more complete statistical cross-correlation with Spitzer Galactic surveys (GLIMPSE and the coming MIPS GAL survey release).

In collaboration with S. Casassus (U de Chile), Hales is studying the radio continuum of Herbig Ae/Be stars in the 26–40 GHz band using the Caltech Continuum Backend (CCB) mounted on the GBT. 16 targets were observed, of which 8 reported positive detections. Preliminary analysis indicates that 50% of the positive detections have gas-dominated (free-free) circumstellar envelopes, while the remaining sources appear to have 1cm continua mostly dominated by a dusty circumstellar disk. Identification of such dust-dominated pre-main sequence objects is crucial for the execution of the proposed eMERLIN

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Legacy Program PEBBLES, aimed at characterizing the dust content in the planet forming region (project led by J. Greaves (PI, St Andrews, UK), in collaboration with 26 others). eMERLIN will allow to image protoplanetary disks down to the scale of the Earth-formation zone in nearby star-forming regions, plus sensitivity to detect a few earth-masses of dusty raw material (C-band). A letter of intent was submitted to the eMERLIN Legacy Steering Group, with a positive response, and a final proposal is now being drafted

In collaboration with S. Casassus and D. Wilner (CfA), Hales led a project aimed at surveying the CO content of 28 protoplanetary disks, Positive detections would be perfect candidates to built up a sample of southern gas rich disks that can be targeted with ALMA. For this project three nights were allocated on the 10 m Atacama Submillimeter Telescope Experiment (ASTE, NAOJ), located in Pampa La Bola. Only one third of the time was usable due to bad weather; the proposal will be re-submitted this fall. One out of eight observed objects had a positive CO detection, confirming its 'primordial disk' classification, originally based on Spitzer and Optical Spectroscopy Data. SMA data for this object was recently acquired by the group, in which they detect the dust continuum but no CO emission. The single-dish CO detection will be incorporated in a full radiative transfer modeling of the disk's structure (as part of M. Hughes' dissertation (CfA)).

Hales, Barlow, and Crawford conducted a search for CS gas absorption in a sample of debris disks using optical echelle spectroscopy at the Anglo-Australian Telescope. Follow-up data of the tentative gaseous disk detections using the 6.5 m Magellan telescope has recently being acquired (June 2008, in collaboration with S. Casassus, U de Chile). In addition to providing higher spectral resolution and sensitivity than previous observations, the new data includes several line-of-sight calibrators that were observed in order to rule out possible interstellar contamination in the target data.

The next most important step after forming prebiotic species in the ISM is investigating the transport mechanism to early planets. Over the last several years, Anthony Remijan and his colleagues have been leading the efforts in the detection of molecular species in comets both with single dish telescopes and with interferometric arrays. These observations have been in collaboration with Milam, S. N., Ziurys, L. M., Apponi, A. J. (University of Arizona), Wyckoff, Susan (Arizona State University), Snyder, L. E. and Friedel, D. N. (University of Illinois), Womack, M., Gesmundo, M., and Choi, S. (St. Cloud State University), Palmer, Patrick (University of Chicago), Woodney, L. M. (California State University), A'Hearn, Michael F. (University of Maryland), and Forster, J. R., Wright, M. C. H., and de Pater, I. (University of California, Berkeley). What they have found are clear differences in the chemical composition of comets. As such, they have started to build up a database for species detected in comets. With enough data, and looking at the formation models of comets in disks, it is possible to differentiate classes of comets based on their chemical composition, where they formed in the disk, and if further processing was necessary to account for any over(under) abundance of a particular molecular species. Their most recent results outline the excitation, formation, and distribution of the cometary species, methanol (CH<sub>3</sub> OH), methyl cyanide (CH<sub>3</sub> CN) and ethylene glycol [(CH<sub>2</sub> OH)<sub>2</sub> ], each of which are important prebiotic molecular species. This is all in addition to high resolution observations that are necessary to more accurately determine whether a species is a daughter or parent molecule.

Over the next year, they will investigate the sulfur and nitrogen chemistry in comets as it pertains to the formation of larger organic molecules. Finally, they have started work on a global monitoring project of short period and, when available, long period comets. This proposal will not only take advantage of current NRAO instruments including the GBT and VLA but also the ASU 12 m, the Onsala Space Observertory 20 m, CARMA, MOPRA and the ATNF to name just a few.

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## **Astrometry**

Amy Mioduszewski, in collaboration with L. Loinard, L. F. Rodriguez, and R. M. Torres at UNAM, has a very large project to carry out an astrometric study with the VLBA of pre-main sequence stars in nearby star-forming regions. The original aim of this work was to obtain accurate distances to the Taurus and Ophiuchus clusters. This has been very successful, distances to stars in the Taurus star forming region have been obtained to the  $\sim 0.5\%$  level and the Ophiuchus star-forming region to the  $<5\%$  level, when previous distances were only good to  $\sim 20\%$ . Much of this work is part of R. M. Torres' doctoral thesis (expected completion summer 2009). With that portion of the project mostly complete it has been expanded in several directions. First, many of the sources turned out to be multiples which, with further VLBA observations, allows a study mass and dynamics of these individual star systems. Second, the Cepheus, Perseus, and Orion clusters have been added to the project, in order to obtain accurate distances to all close by star-forming regions. Lastly, a project to search for more stars in Taurus has been started so that a three dimensional distribution and kinematics of the cluster can be studied. This, combined with pre-main sequence evolutionary models, will allow the distribution of stars with respect to their age to be studied, establishing the history of the star-formation in this important nearby star-forming site.

James Miller-Jones, Vivek Dhawan, and Walter Brisken, together with P. Jonker (SRON), G. Nelemans (Nijmegen) and S. Portegies Zwart (Amsterdam) have measured the proper motion of the black hole X-ray binary V404 Cyg, using HSA observations and archival VLA data. They will use this to trace the evolutionary history of the black hole system back to the time of the supernova explosion, in order to constrain the presence of natal kicks and hence the black hole formation mechanism. Should there be sufficiently high-resolution data in the VLA archives, three other black hole X-ray binaries have been identified where a similar technique could be applied. More statistics on black hole proper motions (V404 Cyg was only the fifth black hole X-ray binary system for which the proper motion has been determined) would help constrain theoretical models of black hole formation. With an REU student, C. Sakari (Whitman College), Miller-Jones has also measured the proper motion of the X-ray binary Cygnus X-3. This provides important input for determining the core position in high-resolution VLBI studies of the system, allowing a more accurate interpretation of the jet morphology. With Fender and V. Tudose (Amsterdam), they will re-interpret new EVN and archival VLBA data, in order to properly understand the complex interactions between the jets and their environment. They will also seek to measure a radial velocity for the system, so the full three-dimensional space velocity of the system can be determined, providing constraints on the natal kick of the system, and hence, possibly, on the nature of the compact object in this well-studied yet poorly-understood system.

In collaboration with Andreas Brunthaler (Max-Planck Institut fuer Radioastronomie), Lister Staveley-Smith (U Western Australia), and Tony Beasley (ALMA) Juergen Ott will continue to measure the positions of water masers in the Large Magellanic Cloud with the Australian VLBI network. After a few more epochs of observation, the proper motion of the LMC will be established and dynamic models of the interaction with the Small Magellanic Cloud and the Galaxy will be developed.

## **Instrumentation and Algorithm Development**

A. Kerr, E. Bryerton S.-K. Pan, and S. Srikanth are working on low-noise receivers for submillimeter wavelengths. In collaboration with the University of Virginia Microfabrication Laboratory, sideband-separating and balanced SIS mixers are being developed for 385-500 GHz and 780-950 GHz based on AlN SIS junctions and NbTiN superconductors. A submillimeter-wave test facility is being constructed which will be used to measure these mixers and will be suitable for future submillimeter receiver work.

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Based on a Sumitomo closed-cycle 4-K refrigerator, it will include LO and signal sources, supporting electronics, a reconfigurable input optics unit, and multiple IF channels to enable the measurement of balanced and sideband-separating front-ends.

Low-loss front-end components are essential for submillimeter wavelength receivers. Bryerton is developing superconducting quadrature hybrids for operation up to  $\sim 1$  THz, and S. Srikanth and A. Kerr are exploring a waveguide orthomode transducer scalable for use to  $\sim 1$  THz.

The lack of viable waveguide and flange standards above  $\sim 110$  GHz is increasingly an impediment to instrument development. Kerr is active in the IEEE Working Group on Waveguides for Millimeter and Sub-Millimeter Wavelengths, whose charter is to develop internationally accepted waveguide and flange standards for the frequency range 110 GHz to 1.1 THz.

In collaboration with NGST, Bryerton will continue to develop MMIC low-noise amplifiers using NGST's new 35 nm InP HEMT process. Based on the record low noise temperatures obtained from 78-95 GHz using this device at cryogenic temperatures, Bryerton will modify the cryogenic device model and use it to retune the current amplifier for 67-90 GHz (ALMA Band 2) and design a new amplifier for 84-116 GHz. By investigating scaling of the transistor gate periphery, Bryerton will also design amplifiers for 18-26 GHz and 31-45 GHz (ALMA Band 1).

Marian Pospieszalski will lead the production and testing of all amplifiers for EVLA receivers and for new receivers for the GBT. All of the amplifiers covering the current EVLA and GBT bands in the frequency range from 1–50 GHz exhibit the best-ever demonstrated noise performance, as yet unmatched in most bands by MMIC designs. The last two frequency bands that will be developed this year are the demonstration amplifiers for Band 1 and Band 2 of ALMA. A study of the feasibility of using high temperature superconductor (HTS) passive circuits in L-band and S-band balanced amplifiers will also be initiated this year.

Pospieszalski will investigate the noise-performance limits of emerging new technologies; that is, the deep submicron (35 nm gate length) InP HFET technology and InP and SiGe HBT technologies in order to assess whether further improvements of significance to the noise and  $1/f$  gain fluctuation performance of radio-astronomy receivers are possible. Further research will also be conducted into some general noise properties of these devices that should establish practical limits of noise performance of amplifiers integrated with broadband feeds currently considered for the SKA.

Some redesign for manufacturability of L-band and S-band balanced amplifiers and also study of using HTS circuits at the input of L- and S-band amplifiers are planned for 2009.

Matt Morgan and J. Rick Fisher are experimenting with integration of analog, digital, and photonic components in compact packages to improve front-end performance and better enable focal plane arrays. Following up on the successful demonstration of digitally-enhanced single-downconversion sideband separation at 4-12 GHz in a laboratory setting, they intend to demonstrate this technique at L-band in a compact package with broader IF bandwidth and in an RFI-rich environment. They will also demonstrate digitally-enhanced polarization isolation at X-band using a four-probe OMT. Long term goals include the integration of the digitizers into a common package with the analog electronics, addressing the isolation issues that come with it, as well as a fiber-optic modulator to create an RF-in digital-fiber-out receiver module.

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Morgan will continue exploration of differential low-noise active baluns, which can be noise-matched to the impedance of log-periodic decade-bandwidth antennas. Currently this study is focusing on the low-loss, high-impedance transition between the feed terminals and the active balun circuit.

Morgan and Bryerton will continue the development of wideband MMIC power amplifiers for millimeter-wave local oscillators. Preliminary results with the first run of a developmental short-gate-length GaAs process are very encouraging. In the coming year these new designs will undergo further RF tests, and revised designs will be generated based on these results.

Morgan will develop ultra-wide IF-band downconverting MMIC mixers for cm-wave radio telescopes such as the SKA and FASR. These so-called “block-conversion” mixers are about the only commonly-required components for radio astronomy in the cm-wave range that are not easily found in commercial MMIC product listings.

Richard Bradley will continue to head the Dynamic Spectroscopy Group of the NRAO Central Development Laboratory. Both undergraduate and graduate students will participate in a variety of analysis, synthesis, evaluation, and observation activities associated with initiatives designed to integrate technology R&D projects with frontier science objectives.

Bradley will continue to serve as interim project engineer for the new Frequency Agile Solar Radiotelescope (FASR) project. This year’s goal is to develop a complete FASR B RF / IF subsystem. A prototype of the wide bandwidth, conical sinuous feed for FASR B will be developed. A proof-of-concept for the FASR A feed will also be fabricated. A cryogenic version of the 0.3–3.0 GHz sinuous feed with an integrated amplifiers will be fabricated and evaluated for use with transient search receivers. The thermal conductivity of rigid foam samples at cryogenic temperatures will also be measured in a specially-developed test Dewar.

The design and deployment of the Precision Array to Probe the Epoch of Reionization (PAPER) will continue in collaboration with D. Backer (UC Berkeley), C. Carilli, and several graduate students. Bradley will continue to lead the R&D activities surrounding the design of specialized antennas, amplifiers, and receivers suited for the project. Bradley and Backer were recently awarded additional funds to support this effort over the next three years. Additional activities associated with PAPER include exploring the use of satellite downlink signals for in situ antenna beam mapping and ray tomography of the ionosphere. Precision tests of receiver stability and a study of active gain correction are also being conducted. Bradley is also participating in a NASA-funded collaboration led by J. Hewitt (PI, MIT) to develop a concept for the Lunar Array for Radio Cosmology (LARC).

S. Srikanth will continue his contribution to the needs of the EVLA and the GBT K-band array project. He will work on the development of a compact ortho mode transducer for the 8-12 GHz band for the EVLA. Due to the limited space available on this receiver, he will also investigate the design of a phase shifter shorter in wavelength compared to the K- and Ka-band phase shifters. Prototyping and measurement of the Ku-band (12-18 GHz) phase shifter will also be carried out.

A design of a dual-band (290–395 MHz and 680–920 MHz) prime-focus feed for the GBT yielded a gain/system-temperature ratio of <70% of that achieved with single-band feeds. Srikanth will continue work in this area to improve the gain/system temperature ratio. Srikanth will start the development of smooth-wall horns as an alternative to corrugated horns for millimeter and sub-millimeter wave

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applications. Development of feeds with about 3:1 bandwidth ratio for centimeter wave astronomy will begin.

Srikanth will collaborate with researchers at the Ohio State University in modifying the OSU reflector code to analyze antennas with shaped reflectors such as the VLA and VLBA antennas.

J. R. Fisher will concentrate mainly on technical R&D associated with RFI mitigation, low-noise beam-forming arrays, and other problems associated with increased field of view at sensitivities now achieved with single-beam receivers. This will include continued implementation of RFI mitigation algorithms in real-time hardware; development of new RFI algorithms; collaboration with BYU colleagues on developing and experimentally verifying a comprehensive model of beam-forming array mutual coupling, noise parameters, and signal processing optimization; replacement of most analog receiver components with digital signal processing; and reducing the size, weight, complexity, and power dissipation requirements of very low-noise receivers.

Robert Reid is extending the smear fitting deconvolution method to take advantage of multifrequency data, motivated both by the upcoming EVLA and a current need to make better rotation measure and spectral index maps. Reid has also begun work on a post-observation algorithm to correct pointing errors for mosaiced observations that he expects will be especially useful for ALMA, which has a small primary beam.

Steve Myers is working with J. Sievers, Ue-Li Pen, and Tzu-Ching Chang (CITA) on the development of new and powerful data analysis techniques with which to analyze interferometric observations of the redshifted 21 cm hydrogen line. This is based on the CMB power-spectrum analysis developed for the CBI project. This is being first applied to the 150MHz GMRT observations of Pen's group, with later extension to the PAPER project of Don Backer and his group (UC Berkeley), which also includes Chris Carilli and Rich Bradley (NRAO).

As the Instrumentation Scientist for the GBT's Precision Telescope Control System, Todd Hunter is working with Brian Mason and Bojan Nikolic (Cambridge) to further develop the out-of-focus holography technique to take advantage of the 64-pixel Mustang focal plane array. This technique has the potential to quickly measure thermal surface deformations due to solar heating, determine corrections for the GBT active surface, and thereby extend efficient 3 mm observing into the daytime hours. Hunter is also working with Fred Schwab, Frank Ghigo, and Steve White to improve the small-scale surface accuracy of the GBT via traditional holography by mapping Ku-band satellite beacons. In addition to surface improvements, Hunter is attempting to make astronomical use of the quadrant detector which measures the pose of the feedarm with respect to the primary reflector. He is mentoring UVA graduate student Paul Ries who has developed an empirical model of the quadrant detector based on half-power tracks which he is testing by applying the results to Mustang images obtained under windy conditions. Finally, Hunter is also serving the ALMA project in the newly-created position of North America Front End Project Scientist. He will work with the receiver engineers at the NTC to identify and examine the critical performance issues during front end integration.

In collaboration with Bill Cotton at NRAO and MUSTANG team members at U Penn, Brian Mason is developing practical, high-fidelity imaging algorithms for the MUSTANG bolometer array on the GBT.

Bill Cotton will continue development of interferometric calibration and imaging techniques are anticipated. In particular, techniques needed for the EVLA will be studied.

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Leonid Kogan has designed an algorithm to optimize array configurations minimizing side lobes of the beam pattern (coded in AIPS as task CONF1). This algorithm has been successfully used for EVLA E-configuration and for ALMA configurations. He has designed the six configurations for LWA's antenna stations with different spacing between the dipoles, and now plans to participate in final choice of the configuration taking into account mutual coupling between dipoles.

As a member of AIPS group, Kogan continues designing new algorithms for calibration and data reduction. Kogan continues investigating new possible algorithms for wide field of view. In particular, he has designed the new algorithm for wide field of view at snapshot observations using a plane array (VLA, for example).

Miller-Jones continues to retain an involvement in the Transients Key Project for LOFAR, the Low Frequency Array, currently under construction in the Netherlands. Before coming to NRAO, he worked as part of a large team, led by Fender, R. Wijers (Amsterdam) and Stappers, to develop a transient detection and response pipeline for low-frequency transients. He still takes part in the monthly meetings and provides some input and assistance for the pipeline development and testing.

Jonathan Romney will continue to lead the VLBA Sensitivity Upgrade project. Collaborators among the scientific staff include Walter Brisken and Craig Walker. This project will expand the data path of the VLBA to a capacity of 4 Gbps, 16 times what can be recorded and correlated with existing VLBA equipment, for a fourfold increase in the instrument's continuum sensitivity. The 4-Gbps target is matched to 2-bit Nyquist sampling of the full 500-MHz bandwidth of the two IF bands normally used. Developments leading to this goal are actively being pursued in three separate, largely independent areas. A new "digital backend," based on modern FPGA technology, will replace the VLBA's existing baseband converters and samplers, and support both a broadband polyphase filterbank and a digital downconverter with 8 independently tunable sub-bands covering bandwidths from 1 MHz to 256 MHz. A new "Mark 5C" recording system will expand the bandwidth of the Mark 5A system currently in use to the required 4-Gbps. A new, software-based "DiFX" correlator will replace the VLBA's original hardware correlator, and provide substantial enhancements in terms of spectral resolution, flexibility, and optimal use of processing resources. All three developments are expected to be sufficiently complete to support high-priority scientific observations at a peak rate of 4 Gbps by the end of FY 2009. Expansion of the sustainable duty cycle to full-time 4-Gbps operation will require only additional recording and processing resources, with a target completion date of 2011.

K. I. Kellermann has been working with an international team to define the next generation radio telescope, the Square Kilometre Array (SKA) which will bring unprecedented sensitivity to a wide range of investigations ranging from pulsar timing and gravitational physics, cosmology including the EoR and continuum and HI emission from high-z galaxies and the evolution of star formation and AGN and their interdependence, and the Galactic magnetic field through Faraday Rotation studies. Kellermann currently chairs the international SKA Science and Engineering Committee and its Executive committee with broad responsibility for the design and governance of the SKA program. During the next year, he will be working with the newly formed SKA Project Development Office located in Manchester, UK to further develop the design and to define the science program. In addition, Kellermann is also chair of the Operations Working group with responsibility for developing an operations plan for the SKA as well as to identify operational procedures that will affect the design, construction, and cost of the SKA. He is also one of two representatives from NRAO to the US SKA Consortium which supports the SKA design and development effort in the US aspects of space VLBI. In particular he investigates the possibility of

improving of the sensitivity of space VLBI adding the acceleration term at the delay model. Kogan will investigate the special methods of imaging for space VLBI.

Scott Ransom will continue to develop his pulsar data analysis package PRESTO, which is in use by many pulsar groups around the world for pulsar searching and timing. The software is available freely from the NRAO website.

Ransom is also the project scientist for the new GBT pulsar backend GUPPI (Green Bank Ultimate Pulsar Processing Instrument). GUPPI is based on the modular and “open-source” hardware (FPGA related) and software tools developed by the CASPER group at UC Berkeley (D. Werthimer, PI). That instrument, when complete by spring of 2009, will dramatically improve all aspects of pulsar observations at the GBT, including much improved timing precision for the gravitational wave searches of NANOGrav. Several other observatories have expressed interest in copying the machine when complete.

Ransom is also working with R. Johnson of UC Santa Cruz to develop new algorithms to search for gamma-ray pulsars blindly in extremely sparse event data from the *GLAST* mission. These algorithms will also be applied to new and archival X-ray data from *Chandra*.

Ronald Maddalena will work in collaboration with Toney Minter, C. Figura (Wartburg College), S. Hynes (Louisiana School for Math, Science and the Arts), and C.H. Johnson (Breck School) to develop new calibration algorithms for single-dish spectral-line observations. The new algorithms are needed owing to the wider bandwidths now in use by radio telescopes. The algorithms provide much higher precision than previous versions while reducing the spectral baselines even when observing continuum sources. The algorithms also correct for second-order nonlinearities in the telescope hardware.

Maddalena continues work on using vertical weather profiles to model the influence of the Earth's atmosphere on observations taken at frequencies below 110 GHz. This includes improved models for refraction, air mass, and the mean atmospheric temperature. The opacities derived from vertical weather profiles have the necessary accuracy for calibration, eliminating the need for antenna tipping or a tipping radiometer. Vertical profiles provide 60-hr forecasts of opacities and system temperatures that are useful predictors for dynamically scheduling the GBT.

Adam Deller will continue development of the DiFX software correlator which will replace the VLBA hardware correlator as part of the VLBA sensitivity upgrade which, when completed, will increase the maximum recording bandwidth of the VLBA eight-fold. He plans to use the high sensitivity of the upgraded VLBA to undertake a large pulsar astrometry program, which will include development of improved tools for the use multiple in-beam calibrators.

## **Miscellaneous**

The next generation of powerful radio and millimeter/submillimeter observatories (e.g., EVLA, ALMA, SOFIA & Herschel) require extensive resources to help identify spectral line transitions. As such, Anthony Remijan and Andrew J. Markwick-Kemper of the University of Manchester continue to develop and expand on a complete spectral line catalog that can be used by the entire astronomical community using current and upcoming radio and millimeter/submillimeter observatories. The Spectral Line Catalog (Splatalogue) is a comprehensive transition -resolved compilation of observed, measured and calculated spectral lines. Extending the JPL and CDMS lists with the addition of the Spectral Line Atlas of Interstellar Molecules (SLAIM) and updating the Lovas/NIST list of observed astrophysical transitions,

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Splatalogue also adds atomic and recombination lines, template astronomical and laboratory spectra, and is completely VO-compliant, queryable under the IVOA SLAP standard. From a querying point-of-view, Splatalogue has two major modes of operation—one user-friendly, the other application-friendly. The former is a PHP based web interface, from which most of the output presented in the following proposal herein came. The latter returns results of IVOA-compliant queries in VO-table XML. Clearly there is scope for other data formats as well. Finally, Splatalogue has already been under development at the North American ALMA Science Center (NAASC) since 2006, even before the needs articulated by the Submillimeter and Far-Infrared Laboratory Spectroscopy Workshop conducted in Pasadena, California, October 19-20, 2006, and in the report from the 2006 NASA Laboratory Astrophysics Workshop (<http://www.physics.unlv.edu/labastro/whitepaper.html>) which stated, “Databases of atomic, molecular, and solid state parameters that are complete [...] and critically evaluated are a necessity.” The work on Splatalogue is overseen by the ALMA Working Group on Spectral Line Frequencies (AWGSLF) that was convened on July 27, 2006, whose mission statement is, “The ALMA Working Group on Spectral Line Frequencies is dedicated to generating a collated and rationalized database of spectral line frequencies, transitions, and line strengths from radio to infrared wavelengths that can be freely accessed and used by the entire astronomical community interested in spectral line astrophysics.” Version 1.0 of Splatalogue is scheduled for release in the Fall of 2009.

Jim Condon and Scott Ransom will continue to develop their on-line radio astronomy course “Essential Radio Astronomy (ERA).” ERA is a one-semester course intended for astronomy graduate students and advanced undergraduates with backgrounds in astronomy, physics, or engineering. The goal of ERA is fostering the community of researchers using radio astronomy by attracting and training the most talented university students. Therefore, we are making ERA available via the web (<http://www.cv.nrao.edu/course/ast534/ERA.shtml>) at no cost. In 2009 we will prepare a book version of this course for publication by Princeton University Press.

Ken Kellermann together with E. Bouton is continuing studies of the history of radio astronomy, with particular emphasis on the formation and early history of NRAO based on archival records and the study of correspondence and files being collected at the NRAO archives. Research during the coming year will include records located at the National Archives of Australia, the Carnegie Institute, and the Library of Congress. They will begin collecting oral histories from the key figures that shaped the early development of NRAO.

Miller Goss and R.X. McGee (CSIRO retired) will publish their book “Under the Radar - Ruby Payne-Scott, the First Woman Radio Astronomer” in the course of 2009. This project was begun in 1999 and finished in 2007 during a visit by Goss to Australia. The book contains a detailed summary of Payne-Scott’s contributions to solar physics in the years 1944 to 1951 as well as other aspects of her life (1912-1981). Payne-Scott is one of the discoverers of Type I and Type IV bursts and played the key role in the first detection of Type II and especially Type III bursts.

Goss and Claire Hooker (University of Sydney) have started a biography of J. L. Pawsey and J. G. Bolton, pioneers of Australian radio astronomy. Both played significant roles in the development of US radio astronomy. Bolton was the founder of radio astronomy at Caltech in the early 1950s and an advisor to AUI until he returned to Australia in late 1960. Bolton became the leader of the newly completed Parkes 64 m radio telescope (opened late 1961). Pawsey had been the science leader of the Australian radio astronomy efforts since 1944. He was offered the job as the second NRAO director to start October 1, 1962. During a visit to Green Bank in spring 1962, Pawsey became ill and returned to Australia where he died on November 30, 1962.

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Interview and archival research for this project began in 2007 and will continue for some years. In the next year archival research in Sydney, Canberra, and New Zealand (the 1948 New Zealand Radio Astronomy Expedition) will continue.

## *C. Research Staff*

### **Research Staff With Tenure**

T. S. Bastian—Solar/stellar radiophysics, solar chromosphere, coronal energy release, solar flares, coronal mass ejections, interplanetary radio bursts, radio propagation in the interplanetary medium, radio emission from late-type stars, substellar objects, and exoplanets; Frequency Agile Solar Radiotelescope (FASR) planning and development.

C. Carilli—Galaxy formation, radio galaxies, QSO absorption lines, epoch of reionization; Chief Scientist.

J. J. Condon—Dark energy, Hubble constant, nearby galaxies, evolution of star formation, radio surveys, GBT precision telescope control system, GBT dynamic scheduling; Special Assistant to the Director

W. D. Cotton—Extragalactic radio sources, interferometry, cosmic masers, computational techniques for data analysis, scientific support, NRAO sky surveys.

A. S. Evans— Extragalactic, multi-wavelength studies of infrared galaxies, radio galaxies and quasar hosts; ALMA commissioning and NAASC.

J. R. Fisher— Cosmology, signal processing, antenna design, advanced receiver development; NRAO Technical Leader for R&D

E. B. Fomalont—Astrometry, X-ray binaries, deep imaging, relativity tests, VSOP and RadioAstron coordination, VLBA support, CASA testing; Principal Scientist and Deputy Assistant Director for End-to-End Operations.

D. A. Frail—Gamma-ray bursts, soft-gamma-ray repeaters, pulsar/supernova-remnant associations, pulsar wind nebulae, masers, HI absorption and interstellar scattering; Head of the Office of Science and Academic Affairs.

W. M. Goss—Galactic-center studies, galactic masers, pulsars, supernova remnants, nearby galaxies.

K. I. Kellermann—Radio galaxies, quasars, cosmology, radio telescopes; NIO, SKA.

A. R. Kerr—Millimeter-wave receiver development, SIS mixer design, ALMA Project.

H. S. Liszt—Molecular lines, millimeter-wave absorption-line spectroscopy, diffuse clouds, galactic nucleus; foreign telescope travel fund administrator and NRAO Spectrum Manager.

K. Y. Lo—Galactic center, star formation in dwarf galaxies, starburst galaxies and high-redshift galaxies, mega-masers and AGN, Hubble Constant and dark energy, intergalactic medium, microwave background radiation, millimeter- and submillimeter-wave interferometry; Director.

### **Program Plan FY 2009**

F. J. Lockman—Galaxies, Galactic structure, interstellar medium, GB education and outreach; GBT Principal Scientist

S. T. Myers—Cosmology, cosmic background radiation, gravitational lenses, astronomical imaging, ALMA and VLA/EVLA scientific support, algorithm development; CASA Project Scientist.

P. J. Napier—Antenna and instrumentation systems for radio astronomy.

F. N. Owen—Evolution of galaxies, clusters of galaxies, radio galaxies, deep continuum surveys, EVLA.

R. A. Perley—Radio galaxies, QSOs, interferometer techniques; EVLA Project Scientist.

M. Pospieszalski—Microwave and millimeter-wave low-noise devices, circuits and receivers, CMBR radiometers, EVLA/VLBA/GBT/ALMA receiver development support.

D. S. Shepherd—Star formation, molecular outflows, disks around luminous young stellar objects, molecular chemistry, millimeter interferometry and mosaic techniques; Deputy Division Head, ALMA Computing.

J. S. Ulvestad—Seyfert, LINER, and starburst galaxies, extragalactic gamma-ray sources, intermediate-mass black holes; Assistant Director for New Initiatives Office.

J. M. Uson—Cosmology, dark matter, clusters of galaxies, superthin galaxies, spectral synthesis imaging.

P. A. Vanden Bout—Interstellar medium, star formation, high-redshift molecular emission galaxies, galaxy formation/evolution.

H. A. Wootten—Star formation, structure and chemistry of the ISM in galaxies, circumstellar material; ALMA Project Scientist.

### **Tenure-Track Astronomers**

C. Brogan—High-mass star formation, astrochemistry, masers, magnetic fields, supernova remnants, small-scale structure in the interstellar medium, ALMA/NAASC, ALMA CASA subsystem scientist.

B. S. Mason—Observational Cosmology and Cosmic Microwave Background radiation; CMB foregrounds (total intensity and polarization); imaging algorithms; instrumentation development; support for GBT continuum observers; MUSTANG project scientist.

S. M. Ransom—Pulsar searches and timing (especially binary and millisecond pulsars) and applications for basic physics, GBT pulsar infrastructure improvement.

## **Scientist/Astronomy**

D. S. Balser—Galactic structure and abundances, H II regions, planetary nebulae; E2E operations; GBT Dynamic Scheduling; GBT Scientific Support.

D. Barkats—Cosmology, cosmic background polarization. Instrument and calibration development. Polarization interferometry; ALMA Commissioning Scientist.

R. C. Bignell—High-redshift absorption systems, planetary nebulae, polarization, GBT scheduling and GBT Scientific Support.

J. Braatz—Cosmic masers, active galaxies, cosmology, molecular gas in AGNs, scientific software and algorithms, GBT science support.

B. J. Butler—planetary astronomy; Division Head, EVLA Computing Division

C. Chandler—Star formation, circumstellar disks, protostellar outflows, millimeter-wave interferometry; Division Head, Socorro Scientific Services, and Deputy Assistant Director for Science, NM Operations..

M. J. Claussen—Masers, young stellar objects, AGB stars, pre-planetary nebulae, spectropolarimetry, VLA/VLBA user programs, VLA+Pt link support, VLA and VLBA scientific support, EVLA testing.

V. Dhawan—Radio and X-ray observations of microquasars, VLBA astrometry, VLBA user support, and EVLA testing.

R. L. Dickman—Interstellar medium, molecular clouds, gravitation and dark matter; Assistant Director, New Mexico Operations

D. T. Emerson—Nearby galaxies, millimeter-wave techniques and instrumentation, spectrum management, history of microwaves.

F. D. Ghigo—X-ray binary sources, active galactic nuclei, Green Bank Telescope user support, GBT precision pointing and active surface improvements.

A. S. Hales—Protoplanetary and debris disks, evolution of circumstellar gas and dust evolution in environments of planet formation, near-IR polarimetry, multiwavelength surveys of the Galactic plane, radio continuum of Herbig Ae/Be stars.

E. J. Hardy—Cosmology, galaxies, stellar populations; Assistant Director for Chilean Affairs, NRAO/AUI representative in Chile.

J. E. Hibbard—Extragalactic HI, galaxy evolution, merging galaxies, spectral synthesis imaging; NA ARC Manager.

## **Program Plan FY 2009**

T. R. Hunter—High-mass star formation, protoclusters, UCHII regions, hot cores, outflows, masers, millimeter/submillimeter interferometry; GBT PTCS Instrumentation Scientist; ALMA North America Front End Project Scientist.

R. Indebetouw—(High mass) star formation, interstellar medium and molecular clouds, NRAO/UVA Joint Faculty.

P. R. Jewell—Interstellar molecules, and astrochemistry; Deputy Director.

L. Knee—Scientific Interest/Functional Position: Molecular clouds, star formation, protostellar outflows, interstellar medium Test Scientist, ALMA project.

G. I. Langston—Transient event surveys, astrochemistry, tests of particle-physics models, Space VLBI new initiatives, Project Manager for NRAO/MIT/LL Bi-static-Radar Project.

C. Lonsdale—Starburst galaxies, ultraluminous infrared galaxies, active galactic nuclei, galaxy evolution, extragalactic surveys; Assistant Director for the North American ALMA Science Center (NAASC).

R. J. Maddalena—Molecular clouds, interstellar medium, structure of spiral galaxies, high-redshift molecular emission galaxies, single-dish calibration algorithms, radio-frequency weather forecasting; Head, GBT Science Operations.

J. G. Mangum—Star formation, astrochemistry, molecular spectroscopy of comets, ALMA; pre-doctoral, intern, and co-op student programs.

M. M. McKinnon—Pulsars, radio polarimetry, statistics;EVLA Project Manager.

A. H. Minter—Interstellar turbulence and galactic HI, GBT scientific support.

E. Momjian—(Ultra)Luminous IR Galaxies, extragalactic HI surveys, cm-wavelength molecular lines, OH megamasers, VLBI imaging of high redshift quasars, Galactic methanol masers, EVLA testing, VLA/VLBA scientific support.

K. O'Neil—Extragalactic gas and dust, low-surface-brightness galaxies; Head, GBT Program Development; Acting Assistant Director for Green Bank Operations.

J. Ott—Molecular cloud and star formation in nearby active, dwarf, and interacting galaxies; multi-wavelength observations of the ISM in galaxies; galaxy evolution; the Galactic Center; EVLA WIDAR Correlator.

A. B. Peck—AGN, high redshift galaxies, mm/submm astronomy, ALMA; JAO Deputy Project Scientist.

R. Prestage—Head of Technical Services in the Joint ALMA Observatory.

A. Remijan—Astrochemistry, astrobiology, physical and chemical conditions of the interstellar, circumstellar, and cometary media.

## **Program Plan FY 2009**

J. D. Romney—Active extragalactic radio sources, interstellar medium, spacecraft navigation, VLBI instrumentation, VLBA scientific support; VLBA Sensitivity Upgrade Project Leader.

M. P. Rupen—X-ray binaries and transient sources, supernovae, interstellar medium, VLA and EVLA scientific support.

L. O. Sjouwerman—Circumstellar masers and AGB stars, centers of the Galaxy and Andromeda, interstellar masers and SNR/MC interactions; VLA/VLBA data-reduction pipelines in AIPS, VLA/VLBA scientific support.

R. A. Sramek—Normal galaxies, quasars, supernovae, aperture-synthesis techniques, ALMA System Development & Verification.

G. A. van Moorsel—Dynamics of galaxies and groups of galaxies, techniques for image analysis, VLA/EVLA scientific support, EVLA CASA subsystem scientist.

R. C. Walker—Extragalactic radio sources, VLBI, VLBA development, VLBA scientific support, EVLA and SKA design.

J. M. Wrobel—Low-luminosity active galactic nuclei; low-mass active galactic nuclei; astrometry; VLA/VLBA scheduling; Scientific Editor, *The Astrophysical Journal*.

### **Scientist/Research Engineering**

R. F. Bradley—Special-purpose radio telescope systems, low-noise amplifiers, array receivers, adaptive RFI excision, advanced receiver development, and radio-based particle physics; Dynamic Spectroscopy Group Leader and FASR Interim Project Engineer.

W. Brisken—Pulsars, astrometry, VLBI software correlation.

E. W. Bryerton—Advanced detector development, technologies for large focal-plane arrays, ALMA local-oscillator development.

J. Cheng—Structural design and analysis, astronomical telescope design, sensors, carbon-fiber material, ALMA antenna development.

A. Lichtenberger—ALMA and the Central Development Lab; NRAO/UVA Joint Faculty.

M. Morgan—Millimeter-wave MMIC design, MMIC-based instrumentation, arrays, and receiver component development for the EVLA, GBT, ALMA, FASR, and SKA.

S. K. Pan—Superconducting millimeter- and submillimeter-wave low-noise devices, circuit and receiver development; Deputy Assistant Director, CDL.

K. Saini—ALMA local-oscillator development, frequency-multiplier development, ALMA Front-End System engineering.

### **Program Plan FY 2009**

S. Srikanth—Development of polarizers for mm-wave applications and broadband prime-focus feeds at centimeter wavelengths.

J. C. Webber—Instrumentation development, program planning; Assistant Director for CDL; ALMA IPT Leader for Front End and Correlator.

### **Scientist/Computational Science**

J. M. Benson—Extragalactic radio sources, VLBA image processing, scientific support for VLA/VLBA correlator, development and maintenance of the NRAO Science Data Archive, member of the E2E-EVLA Computing Group.

S. Bhatnagar—Supernova remnants, HII/UCHII regions, low-frequency mapping of the Galactic plane, interferometric calibration, image reconstruction, and related algorithm development, CASA.

K. Golap—Low-frequency calibration and imaging, imaging algorithm development, CASA.

E. W. Greisen—Radio galaxies, HI in galaxies, interstellar medium, computer analysis of astronomical data, AIPS.

L. R. Kogan—Theory of interferometry including space VLBI, design of array configurations (LWA, SKA), VLBA user support, AIPS group.

J. P. McMullin—Star formation, interstellar medium, astronomical software systems; ALMA CIPT offline-subsystem lead, Science Software Group Project Manager.

A. J. Mioduszewski—Astrometry of young stellar objects, microquasars, symbiotic stars, AIPS, VLBA, HSA, and VLA support, student programs.

G. Moellenbrock—Polarization interferometry, VLBI techniques, astrometry, blazars, calibration and imaging algorithms, software for ALMA and EVLA, VLA and VLBA user support.

R. I. Reid—Automated data analysis, interferometric imaging, the warm ionized medium, radio galaxies.

### **Scientist/Emeritus**

A. H. Bridle—Extragalactic radio sources, Computing and Information Services web support, inter-site communications support, pre-doctoral, intern, and co-op student programs, and visiting-scientist support: Emeritus Scientist.

B. G. Clark—EVLA control and software development, VLA/VLBA scheduling; Emeritus Scientist.

M. A. Gordon—CO, galactic structure, gas-rich galaxies, interstellar medium; Emeritus Scientist.

D. E. Hogg—Structure of spiral galaxies, stellar winds, general support for the Director's Office, Emeritus Scientist.

### **Program Plan FY 2009**

M. S. Roberts—Extragalactic hydrogen, normal galaxies, dark matter; Emeritus Scientist.

A. R. Thompson—Radio-astronomy instrumentation, theory and practice of radio interferometry and synthesis imaging, interference mitigation and spectrum protection for radio astronomy; Emeritus Scientist.

### **Jansky Fellows**

E. D. Araya—Cosmic masers; massive star formation; molecular clouds and interstellar medium; starburst galaxies and AGN; Jansky Fellow.

A. Chung—Galaxy formation and evolution, cluster environmental effects, radio/sub-millimeter instrumentation; Jansky Fellow.

S. A. Corder—Rapid accretion events from low mass stars, outflow feedback in star-forming regions, debris disks and the search for young planetary systems, techniques in wide-field imaging, ALMA commissioning.

A. Deller—VLBI software correlation, VLBI pulsar astrometry, wide-field image calibration; Jansky Fellow.

P. Demorest—High-precision pulsar timing, gravitational radiation, interstellar scintillation, backend instrumentation development, signal processing; Jansky Fellow.

B. R. Kent—Nearby galaxies and clusters, galaxy dynamics, gas dynamics, extragalactic HI, scientific software, Virtual Observatory; Jansky Fellow.

D. P. Marrone—Galaxy cluster cosmology, Sunyaev-Zeldovich Effect, Galactic center, millimeter/submillimeter interferometry and instrumentation; Jansky Fellow.

J. C. A. Miller-Jones—X-ray binary jets; their morphologies, speeds, energetics and interaction with their environments, low-frequency transient surveys; Jansky Fellow.

W-H. Wang—formation and evolution of galaxies using optical, near-IR, mid-IR, submillimeter, and radio observations; Jansky Fellow.

### **Research Associates and NRAO Postdoctoral Fellows**

M. Aravena—Galaxy evolution, submillimetre galaxies, high-redshift galaxies, relation between starburst galaxies and QSOs, multi-wavelength surveys.

B. E. Hesman—Planetary astronomy, EVLA scientific support; EVLA postdoctoral fellow.

C. M. V. Impellizzeri—Active galaxies, Seyfert, LINER, molecular absorption, water masers; NRAO Postdoctoral fellow.

### **Program Plan FY 2009**

N. Kanekar—Galaxy formation and evolution, damped Ly $\alpha$  systems, OH megamasers, structure of the ISM, the evolution of fundamental constants; MPIfR fellow.

M. Pannella—Galaxy formation and evolution, structural and spectrophotometric properties of galaxies; Research Associate

V. Strazzullo—Galaxy formation and evolution, galaxy clusters; Research Associate.

J. Wagg—Research Associate.