I. *Introduction*

Millimeter and sub-mm wave astronomy have revolutionized our current view of the universe. Molecular clouds were discovered through studies of mm-wave lines of chemical species such as CO and CS (Burton et al. 1975). Mm-wave observations subsequently showed that stars form in these clouds, accompanied by bipolar outflows, protostellar disks and other effects of gas dynamics, as shown in Figure 1. Molecular emission at mm-wavelengths has also helped trace the kinematic structures of both our Galaxy and external galaxies (e.g. Dame and Thaddeus 1994) and define a more complete picture of the "Molecular Milky Way". Mm-wave measurements have also elucidated the later stages of stellar evolution via observations of AGB and post-AGB envelopes (e.g. Glassgold 1996; Young 1997), yielding quantitative estimates of mass loss rates (e.g. Guélin et al. 1996). Similarly, isotope ratios for such elements as carbon and magnesium (Guélin et al. 1995) have given important insights into nucleosynthetic and dredge up processes in AGB stars. Mm-wave astronomy has also resulted in the detection of the vast majority of interstellar /circumstellar molecules, spawning the creation of new field of astrochemistry. Recent advances in this area have included identifications of complex organic species such as vinyl alcohol (Turner and Apponi 2001), and refractory compounds, including SiC_3 (Apponi et al. 1999) and AlNC (Ziurys et al. 2002).

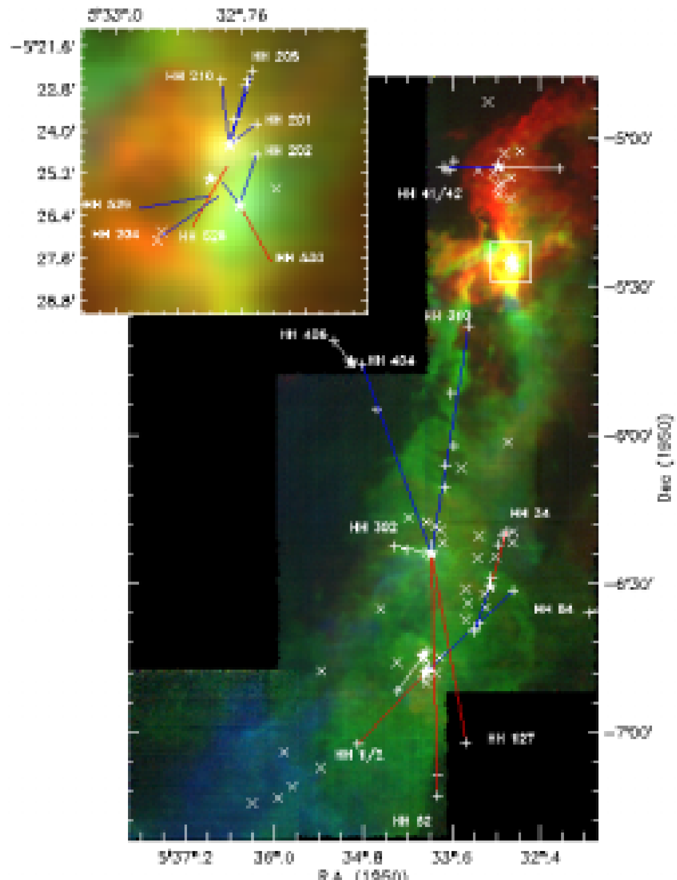


Figure 1. The Orion molecular cloud complex as seen in CO J=2→1 emission measured with the Kitt Peak 12m , overlaid with the location of red and blue shifted outflows and Herbig-Haro objects (Bally 2001).

The mm-wave atmospheric windows at 3 mm (65-115 GHz), 2 mm (125-190 GHz), and 1.2 mm (200-300 GHz) bands are fairly transparent. Many additional spectral regions are accessible to ground-based telescopes at sub-mm wavelengths (see Figure 2). The sub-mm region has been called the last frontier for observational astronomy, since it lies at the overlapping limits of the traditional super-heterodyne techniques of radio astronomy and the incoherent detection techniques (photoconductors and bolometers) of the infrared.

The sub-mm region plays a unique role in addressing many astrophysical problems (Phillips and Keene 1992). Higher transitions of common interstellar tracers like CO and CS occur in this region and probe the warm gas of molecular clouds and indicate possible star formation cores in both our Galaxy and in external galaxies. Higher transitions of large dipole-moment species such as HCN and HCO^+ are also at sub-mm wavelengths and are sensitive tracers of high gas densities, i.e. $n \sim 10^7$ cm^{-3} (e.g. Melnick et al. 2000). Several atomic fine structure lines fall in this spectral region as well, most importantly, the $^3P_1$-$^3P_0$ transition of neutral carbon at 492 GHz. Because $^3P_0$ is the ground state term for CI, carbon can readily be detected via this transition in a variety of environments, including photon-dominated regions, the interclump medium, and the shocked gas of outflows (Frerking et al. 1989; Walker et al. 1993). Diatomic hydrides are also unique to the sub-mm band. These species have large rotational constants because of their relatively small moments of inertia; thus the fundamental transition of SiH (Ω=1/2, J=3/2 →1/2) lies at 665 GHz. Hydrides are fundamental building blocks of interstellar chemistry, and knowledge of their distributions and abundances is critical for evaluating chemical networks (van Dishoeck 1995).

Despite the importance of millimeter and sub-mm astronomy, there are very few telescopes in operation at these wavelengths. Substantial investments have already been made for future instrumentation in mm/sub-mm science, as evidenced by ALMA, LMT, SOFIA, and Herschel. If these facilities are to be fully utilized, the U.S. must maintain a strong presence in the mm/sub-mm field. Since national facilities are no longer actively supporting this science, the universities must keep these areas flourishing through strong research and educational programs.

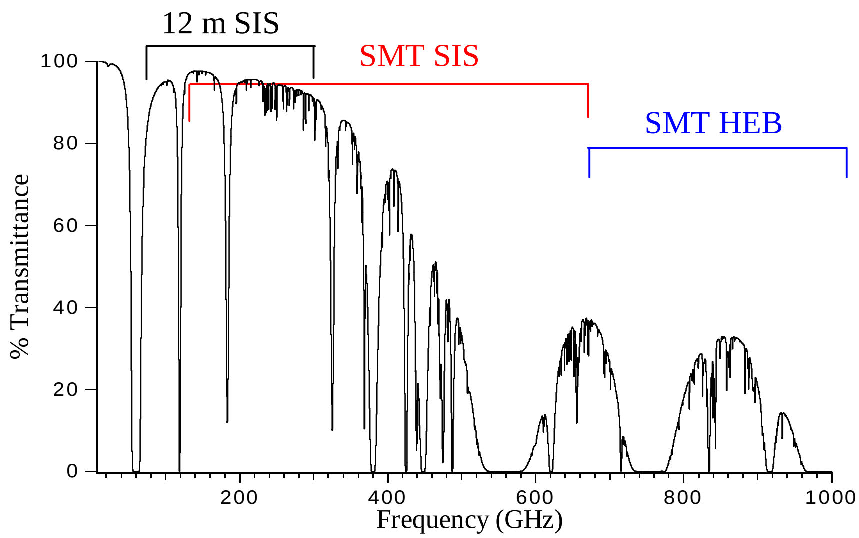


Figure 2. A plot of atmospheric transmission vs. frequency, illustrating the accessible mm and sub-mm windows, and current and planned receiver coverage at the SMT/KP12m telescopes.

The purpose of this proposal is to request partial funding to support the millimeter/sub-mm research of a university consortium involving the University of Arizona (UA), Massachusetts Institute of Technology (M.I.T.) and the University of Colorado using the Arizona Radio Observatory (ARO) facilities. These include the 10 meter Sub-Millimeter Telescope (SMT) on Mt. Graham and the Kitt Peak 12 meter (KP12m) antenna, formerly run by the National Radio Astronomy Observatory (NRAO). The combined telescopes will cover the complete mm/sub-mm frequency range from 65-1000 GHz, and thus provide unique capabilities. The requested funds are mainly to support graduate student and post-doctoral fellows at the participating institutions, and further technical developments at both telescopes by providing crucial capital equipment and salaries for a core engineering staff. Only partial funding is requested because there are matching monies from the UA, Max-Planck-Institut fur Radioastronomie (MPIfR), and from the Research Corporation (RC), in support of science at small colleges. In addition, 50% of the NSF supported observing time will go to external users (~5 months of observing time at two telescopes). Unique components of this proposed program are: (i) mm-wave Very Long Baseline Interferometry (VLBI) observations, carried out using the SMT and KP12m baseline and spearheaded by the M.I.T. group; and (ii) intensive molecular line identification work spanning both mm and sub-mm bands, done in conjunction with the UA mm/sub-mm spectroscopy lab. Individual P.I. research and longer-term, observatory-wide projects are also proposed. The latter include surveys of the Milky Way at 1.3 mm and 0.87 mm. An outreach program involving the education of local high-school teachers is an integral section as well. In the following sections, the details of this consortium proposal are discussed.

II. Background

II.1 Two Complementary Telescopes

One of the two telescopes involved in this proposal is the SMT located on Mt. Graham. This instrument, shown in Figure 3, was constructed as an international collaboration between the UA and the MPIfR, in Bonn, Germany, and saw first light in 1993. As of June 2002, it becomes the property of the UA. This antenna (Baars et al. 1999) has several unique characteristics. The surface consists of molded carbon fiber reinforced plastic (CFRP) panels and is covered with aluminum for high reflectivity. The RMS surface accuracy of each panel is 7 µm. The back-up structure is made of CFRP rods. Therefore, the entire antenna is extremely insensitive to temperature changes and observing is consequently conducted 24 hours a day throughout the 10 month season. Results of repeated holography over the past few years indicate an rms surface accuracy over the

Figure 3. The SMT 10 meter located at Mt. Graham, AZ, the most accurate radio antenna built to date.

entire dish of better than 15 μm. The surface accuracy has not changed significantly between holography runs, indicating a very stable structure. This structure results in a pointing accuracy of better than 2.″5 rms. With the aid of a newly mounted optical telescope, the 1″ rms design goal will be realized in the near future. This antenna is clearly the world's most accurate radio telescope to date.

The SMT offers great flexibility for both facility and experimental instrumentation alike owing to its dual Nasmyth foci, where the signal can be directed into a choice of two large receiver rooms. Consequently, all receivers and bolometers can readily be mounted on stationary optical tables for easy implementation, service, and use. Each room can hold a variety of instruments. For example, currently the left-hand receiver room houses the 1.2 mm, 0.8 mm, and 0.6 mm heterodyne receivers (the first generation facility instruments), and the right hand side contains the 0.8 mm, 19-channel bolometer array, and the 0.8-1.0 THz hot electron bolometer (HEB) systems. The latter is an experimental system, built in collaboration with the Harvard-Smithsonian Center for Astrophysics (CfA), which has been used for 800 GHz and 1 THz observations (Kawamura et al. 2002). Other instruments can be added to this spacious arrangement, as will be the upgraded receiver systems (0.6-2 mm), which are discussed in section IV.

The other telescope that is part of this proposal is the KP12m. Originally built as a 36 ft. dish, this instrument has played a fundamental role in the development of mm-wave astronomy and instrumentation, including the initial detection of CO by Wilson et al. (1970), and many other new molecules. In 1984, the NRAO installed a new surface on the antenna and increased the telescope aperture to its current 12 meter diameter (see Figure 4).

Figure 4 The 12 meter telescope at Kitt Peak has been operated by Steward Observatory for the past 1 1/2 years.

The facility continues to be very productive, partly because of its broad-band frequency coverage (65-300 GHz), its highly efficient control system, a 24 hour-a-day, 7 days-a-week operating schedule, and other advantages such as remote observing and "on-the-fly" mapping. Following NRAO's decision, that it would cease operation of this telescope on July 31, 2000, Steward Observatory (SO) took over operations of the KP12m, with financial support from both the UA and RC. The UA has subsequently received "bridge-funding" from the National Science Foundation (NSF; $400,000 for 1.5 years) and with matching funds from the RC and SO, has continued operation of the KP12m telescope with participation of a broad user community. This group includes astronomers from, Colorado, JPL, NASA Ames, NRAO, IRAM, and the Universities of Tokyo, St. Cloud, Illinois, Caltech (IPAC), Harvard, M.I.T, Mass, Maria Mitchell Observatory, Williams College, Florida, Ohio State, MPIfR, UMIST, Haverford College, Hofstra, CfA, Seoul National, Leiden, Conn. College, Wesleyan, Calgary, St. Mary's, Maryland, Chicago, and most notably U.C. Berkeley where at least 5 graduates are involved in KP12m projects, many of which are complementary to the BIMA array (see section III). In fact, last year more than 50 outside users conducted programs at the KP12m. The KP12m thus has successfully continued in its role of keeping vitality in the mm-wave community at a modest cost.

A summary of the basic properties of the two telescopes is shown in Table 1. The science that has emerged from these instruments is multi-faceted.

Table 1: Basic Telescope Characteristics

	Kitt Peak 12 Meter	SMT 10 Meter
Altitude	1914 m (6280 ft)	3186 m (10454 ft)
Location	Kitt Peak, 53 miles SW of Tucson	Mt. Graham, 75 miles NE of Tucson
Surface Material	Machined Aluminum Panels	Carbon Fiber Reinforced Panels
Surface Accuracy	75 micrometers rms	<15 micrometers rms
Pointing Accuracy	7″ rms	2.5″ rms
Frequency Coverage	65-300 GHz continuous	Current: 210-490, 660 and 810 GHz, Current: 19-channel 870 μm bolometer Future: 129 – 1000 GHz Future: 7-channel 345GHz SIS array

II.2 A Snapshot of Past Scientific Results

The SMT with its highly accurate surface and excellent pointing is truly a sub-mm dish with high frequency (THz) capabilities. This characteristic was clearly demonstrated by the first observations of the J=9→8 transition of CO at 1.037 THz (Kawamura et al. 2002) done with an 8.″5 (FWHM) beam. Spectra were recorded at several positions along the ridge of the Orion molecular cloud, the central position is shown in Figure 5. Remarkably, this transition of CO was detected over a 4′ region, indicating very hot extended gas in the vicinity of Orion-KL. (The J=9 level lies 248 K above ground state). These observations showed the presence of two distinct clouds along the line of sight near BN/KL, as had been suggested by past studies of N_2H^+ (Womack et al.1991).

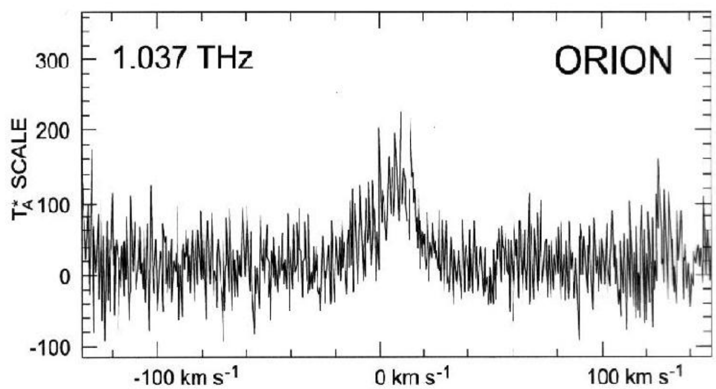


Figure 5 CO J=9→8 spectrum measured at the SMT at 1.037 THz measured along the Orion ridge (Kawamura et al. 2002).

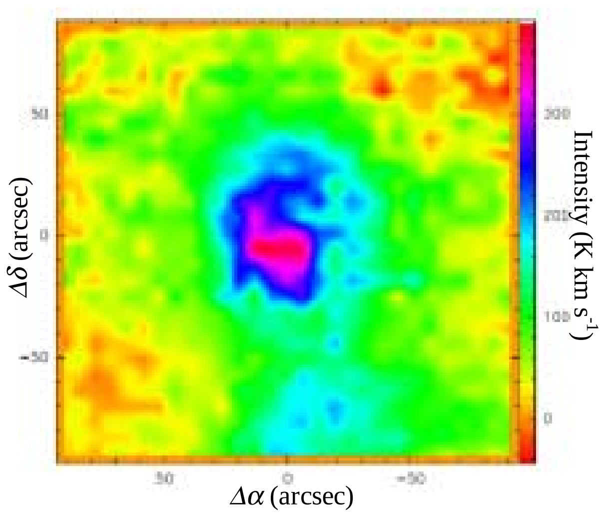


Figure 6 A map of the Orion outflow in the J=6→5 transition of ^{13}CO at 661 GHz, done with the SMT 10 meter (Dumke et al., in preparation).

The high frequency capability of this telescope is also evidenced by numerous observations of the J=7→6 transition of CO near 810 GHz, the J=6→5 line of ^{13}CO at 661 GHz, and the CI lines at 492 GHz and 809 GHz. Various galactic molecular clouds with star formation have been mapped at 810 GHz, including Orion, Cepheus B, Sharpless 106, and ON-1 (Wilson et al., in preparation). The Orion outflow has been imaged in the ^{13}CO: J=6→5 line, as shown in Figure 6. These data show exactly where the hot gas is located, and indicate the relative ages of the various star-forming regions. A similar differentiation in star formation timescales has been evident in CI observations (492 and 809 GHz) taken towards the W3 complex (Tieftrunk et al. 2001). Most interesting has been mapping data obtained towards the outflow source IRAS 20126+4104, where the blue and red shifted CO wings (J=7→6) meet at the precise position of the infrared source—an accomplishment only possible because of the pointing accuracy of the SMT telescope (Kawamura et al. 1999).

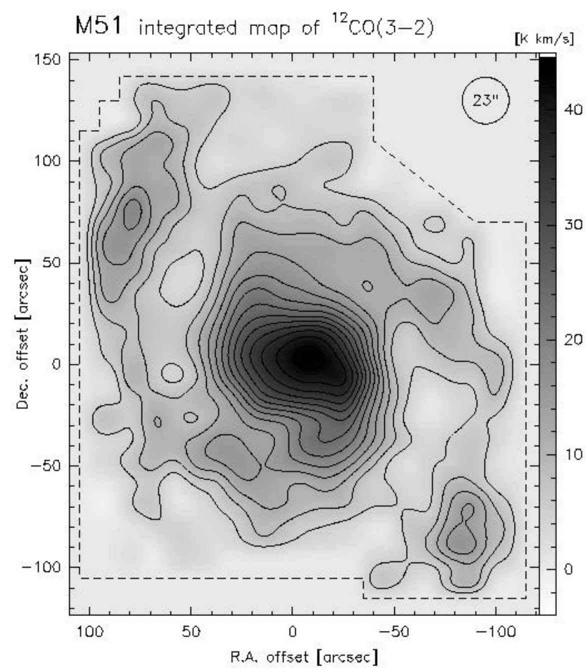


Figure 7 Map of the integrated intensities of the CO: J=3→2 transition, made towards the face-on galaxy M51, using the SMT.

Lower frequency observing at the CO: J=3→2 transition frequency near 345 GHz is routine at the SMT. Studies of this emission towards nearby face-on galaxies such as M51, NGC 6946, and M83 (Mauersberger et al.1999; Dumke et al. 2001; Thuma , in preparation) shows significant structure in the spiral arms and the presence of a warm (T>30K) galactic disk, as displayed in Figure 7. Because the J=3 energy level lies 33 K above ground state, this gas must be warmer than the canonical 10 K observed in most molecular clouds. The source of this additional heating is not known.

Detections of this transition have also been made towards elliptical galaxies, including NGC404 and NGC3593 (Vila-Vilaro, in preparation), indicating significant star formation in these objects. Many of these sources have also been mapped with the 19-channel bolometer (0.87 mm) in order to separate molecular emission from that of dust. Curiously, 10% - 50% of the emission detected with the bolometer arises from CO, depending on the activity of the galaxy (Dumke et al., in preparation).

This work is only a small sample of the science that is currently being conducted at the SMT, using only the first generation of SIS receivers, which are single channel, double-sideband systems at 1.2, 0.8 and 0.6 mm. The higher frequency investigations have been carried out with the HEB that has a NbTiN junction.

Scientific achievements at the KP12m telescope are equally as numerous since Steward Observatory began operating it in the fall of 2000. One of the most recent successes, albeit primarily a technical one, has been the VLBI experiment carried out this April at 2 mm, using the SMT–KP12m baseline. Fringes were cleanly detected at 147 GHz towards the bright AGN 3C279 and at 129 GHz towards the SiO maser source VY CMa—the highest frequency spectral line VLBI to date. The IRAM 30m telescope in Spain joined the SMT/KP12m array and 3C279 was detected from the 30m to both Arizona sites. A fringe spacing of ≤50 μarcsec was achieved in this case—the highest angular resolution ever obtained by ANY astronomical technique. More details of this experiment and its exciting scientific potential are given in Section III.

The KP12m telescope continues its thirty year tradition as a molecule-hunting machine, as evidenced by the recent detections of SiC_3 (Apponi et al. 1999), vinyl alcohol (Turner and Apponi 2001) and possibly KCN (Savage et al., in preparation).

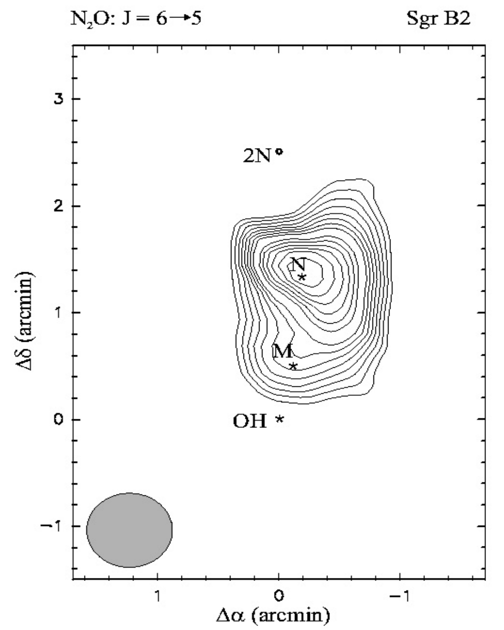


Figure 8 Contour map of the peak line intensity of the J=6→5 transition of N_2O, showing confined distribution centered on SgrB2(N), a result of high-temperature chemistry.

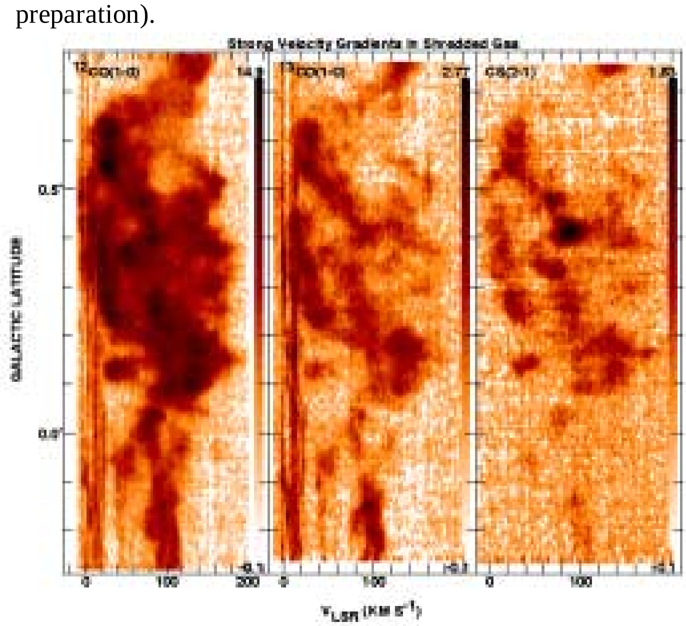


Figure 9 Maps of the J=1→0 lines of CO (left), ^{13}CO (middle), and the J=2→1 line of CS (right), showing broad, yet spatially distinct features more than 30′ across the galactic plane.

Mapping observations of NO and N_2O in molecular clouds have shown that the chemistry is highly spatially dependent. For example, in the SgrB2 complex, 2 mm NO emission is widespread across 5′ of the cloud. N_2O, in contrast, is confined to a 1′ source centered on SgrB2(N) (Halfen et al. 2001). This confinement, shown in Figure 8, is not due to excitation but rather chemistry. Evidently, a reaction with an energy barrier requiring higher temperatures is responsible for the synthesis of N_2O. A similar confined distribution for N_2O has recently been found toward Orion-KL (Halfen et al., in preparation), where this molecule appears to arise exclusively in the so-called "hot core" region. Hence, N_2O is a good tracer of hot molecular cloud cores.

Galactic structure is another area of study for the KP12m. Maps of CO, ^{13}CO, and CS (J=2→1) emission, made by H. Liszt (NRAO), have given three views of an enigmatic aspect of the molecular gas distribution in the center of the Milky Way (see Figure 9). As shown in this figure, along the galactic equator CO emission is primarily localized in a number of sharp "streaks", broad in velocity but only a few tenths of a parsec across—about the width of a single giant molecular core (GMC). These maps also resolve the internal kinematics of these molecules and show that 150–200 km/s wide lines occur more than 30′ (or 75pc) perpendicular (not along) the galactic plane. A Hydrodynamic model of gas flow in a strongly-barred gravitational potential suggests that such broad lines should occur whenever GMC's traverse the standing shocks which cause prominent dust lanes. The small volume-filling factor of molecular gas then accounts for the finite number of broad-lined features.

Another interesting chemistry project concerns the molecular composition of 10 billion year-old gas at the edge of the Milky Way (28 kpc from the galactic center). Using the KP12m, various molecules (HCO^+, HCN, HNC, CO, C_3H_2) were detected in these regions. Emission from nitrogen bearing molecules was typically quite weak, indicating that this element is highly depleted in this gas. The result is consistent with a low metallicity cloud forming from the infall of halo gas enriched in C, O, and S from an early burst of massive star formation, but depleted in the secondary element nitrogen that is only produced by low mass stars (Lubowich et al. 2001).

III. Proposed Scientific Research

The ARO telescopes (SMT and KP12m) offer unique capabilities for mm/sub-mm astronomy that complement those of facilities such as BIMA, OVRO and the SMA. Most important among these is ARO's unrivalled spectral coverage from 65-1000 GHz and its ability to switch rapidly between them. This section describes several long-term key science projects that exploit ARO capabilities and that could not easily be carried out at national facilities. These programs are followed by some brief examples of other programs that will also be carried out at ARO mainly by external scientists during the course of the program period.

III.1 Extragalactic Studies

III.1.1 Extragalactic Survey of 'Normal' Galaxies: The SMT/KP12m Contribution

Background: What is a 'Normal' Galaxy?: It is a bit paradoxical that the study of the interstellar medium (ISM) in the central regions of active and starburst galaxies has brought about a renewed interest in 'normal' galaxies. Several recent observational results of the former have shaken some of the long-standing views on the origin of nuclear activity in galaxies and starbursts so much that a thorough reexamination of the properties of the ISM in 'normal' objects has become necessary:

- **The Luminosity Problem**: It is now clear that both the starburst and active nuclei phenomena cover a huge range in intrinsic emission line/continuum luminosities, merging smoothly into the 'normal' category at their lower ends (Vila-Vilaro 2000).
- **Supermassive Black Holes**: They seem to exist at the centers of *most* galaxies. Therefore, the traditional tenet that nuclear activity occurs only in a minority of objects that possess them no longer holds. For some reason the ISM in the host galaxy ends up accreting on the central black hole triggering the activity, but this can happen to any spiral and it can even be a recurrent phenomenon (Kormendy 2001).
- **What was learned from CO (1→0)**: This molecule is a tracer of the *total* molecular gas mass. Since molecular gas is the most abundant ISM component in the central regions of spirals, it is the best candidate fuel for nuclear activity and starbursts. Several mm-wave single-dish (Vila-Vilaro et al. 1998) and interferometry surveys (Sakamoto et al. 1999) were carried out in the hope that active and starburst galaxies would clearly differ from 'normal' galaxies. However, the overall result is that (except for destructive mergers) the amount and distribution of molecular gas in the central regions of spiral galaxies show no trend with activity.
- **Dusty/Molecular Torus**: Several active galaxies (i.e., NGC1068, M51) seem to possess very high density and temperature central regions (Matsushita et al. 1998; Jackson et al. 1993). Since a popular model that tries to unify all the observational properties of active galaxies in a sequence of pure nuclear luminosity and geometrical orientation effects requires the presence of a toroidal warm and dense ISM near the center of these objects, these detections have sparked a lot of interest. Starburst galaxies also seem to have a much denser and warmer ISM.
- **Old and young starbursts**: M82 and NGC253, the two nearest starbursts, have been studied intensely. Although both are experiencing starburst activity, their molecular emission can only be explained by considering them to be at different ages, with NGC253 being the younger of the two and possessing denser and warmer gas fractions than M82 (Paglione et al. 1997). As a result, a new category of objects has been recently added to the extragalactic fauna—the 'post-starbursts'. These objects are characterized by a lack of dense gas at their centers caused by a recent strong starburst episode and are on their way back to (possibly) becoming 'normal' again.

Although this evidence is still fairly fragmentary, a general scenario is clearly emerging. In a nutshell, it seems that nuclear activity and starbursts are just transitory phases in the evolution of otherwise ‘normal’ galaxies. These transitory episodes are characterized, from the point of view of the molecular component of the ISM, by increases in density and temperature. In the case of starbursts the increase in density is clearly associated with the higher fraction of dense cores needed to form stars and also possibly by repressurization of the ISM due to SN explosions. The temperature increase will be associated with the higher UV fields present in regions near where the stars are born. In the case of active galaxies the situation is not that simple, since density enhancements may come from the formation of the “molecular torus”, or from indirect repressurization by plasma radiojets, X-ray outflows, shocks, etc. Heating also has the same problems because nuclear hard continuum adds up to local phenomena, such as star formation (some objects exhibit *both* an active nucleus and a starburst).

Objectives: Since activity is just a transitory phase in the evolution of ‘normal’ galaxies, as the evolutionary sequence of starbursts seems to indicate, at some stage after the active phase (and possibly prior to it), the host galaxy will come back to its "normal" state. To trace the *true* level of activity of an object then, instead of using the *total* amount of molecular gas present, better tracers of dense gas fraction and temperature of the molecular phase must be used. Moreover, to distinguish the stage of active/starburst object is in, the zero threshold level (i.e., "normal" state) of galaxies with similar luminosity classes and Hubble morphological types must be known. Unfortunately, no systematic study of these properties in a sample of ‘normal’ galaxies large enough to be statistically significant and covering good density and temperature tracers, most Hubble types, and luminosity classes has been done. The main objective of this survey project using the combined power of the SMT and KP12m is to fill this crucial gap. ARO will be observing a sample of well-known completeness (see *Sample Selection*) in several of the optically thin isotopes of CO (i.e., ^{13}CO, $C^{18}O$) as well as in several high-density tracers (HCN, CS and HCO^+). The temperature conditions will be obtained by modeling multiline transitions of the same species. Because rotational molecular transitions at higher frequencies for all the species mentioned above have higher equivalent temperatures to the ground level, combining observations in the mm range (KP12m) with the sub-mm (SMT) will be necessary.

The benefits of such observations are obvious. A consistent database of the properties of the molecular ISM in spiral galaxies of all Hubble types will be available for comparison with active/starburst objects. Once this database is available and ‘average’ properties for each Hubble type are known, a more comprehensive chronological study of starbursts will be possible, with profound implications for our understanding not only of the general evolution of these objects, which will help also in cosmological studies, but also on the possible differences and maximum values that the molecular gas physical conditions can achieve during star formation. In the case of active galaxies, the main contribution will be to the understanding of whether the huge density fractions found at the centers of some of them are actually peculiar or can be achieved by other means. Furthermore, the fact that active objects have a much harder continuum than normal star formation will surely impact in the temperature of the regions and in the relative abundance of ionic species like HCO^+. Therefore, average values of the ratios of these species in normal galaxies will also be needed to distinguish normal conditions. Finally, the database will also be used for interferometric projects that require “zero spacing” corrections to recover total flux, which surely will be necessary in cases like ALMA (with antennas of similar size to the ones used in this survey).

Sample Selection: The Revised Shapley Ames catalog is ideal for our survey because of its well-studied completeness properties, the proximity of the objects in it, and the fact that most of them have already been at least observed in CO ($1\rightarrow0$) by a mm-wave telescope. Furthermore, the recent optical spectroscopy work by Ho et al. (1995) has provided classifications of the nuclear activity class of most of the objects. Finally, they also represent the best-studied sample in other wavelengths (IR, X-rays, UV, and optical), providing a lot of additional information that can be used in the analysis of the data. ARO therefore has decided to use all the galaxies in this catalog that are visible from Arizona, that are classified as spiral, that have been observed in CO ($1\rightarrow0$) and are bright enough to guarantee that emission in weaker transitions can be detected in a reasonable time.

Since all the objects that will be observed are nearby, high-resolution observations are not necessary to ascertain the average properties of the central regions. What is essential for this project is the ability to combine mm and sub-mm wave data with comparable resolutions over a wide range of transitions and species.

This large sample will be divided in three sets of forty objects each. The first step will be observations of the mm-wave transitions of the rare CO isotopes and the brightest density tracers (HCN, HCO^+ and CS). This will give the largest beam sizes that will have to be matched when going into the sub-mm with maps and reconstruction techniques. Only the sub-mm transitions of the detected species will be tried in the 345 GHz and 460 GHz windows. High density tracers will only be observed in the mm-wave range because their critical densities for the sub-mm transitions are very high and therefore will be mapping only small localized regions with small beam filling factors.

The scheduling for the sub-mm observations will be taking full advantage of the 'priority observing' mode at the SMT (see section V.3). At higher frequencies a simple 5-point map will be conducted to cover the beam sizes of the mm-wave observations.

The estimated time per object for at least several transitions of the CO isotopes and 2 density tracers will be about 10-15 hours/object. This will require about 500 hours per year and an estimated completion time of 3 years. The ratios of the transitions of the same species and ratios of CO isotopes to the density tracers will all be compared with LVG and PDR models to determine average physical conditions for the sample as a whole and for breakdowns in morphological types. This project will be led by B. Vila-Vilaro (SO) and A. Zabludoff (UA).

III.1.2 Low Metallicity ISM Laboratories: LSB Galaxies

The existence of galaxies with optical surface brightness close to the night-sky, or low surface brightness (LSB) galaxies, had already been postulated in the 1970s (Disney 1976). No one at the time, however, considered them an important component of the baryonic matter in the Universe, and now it is believed that almost half of the galaxies in the nearby Universe may belong to this class (Bothun et al. 1997).

Multi-wavelength observations of several nearby objects have revealed that, contrary to initial theoretical predictions, these objects cover a huge range of masses from dwarfs to late-type spiral sized objects. In fact, they also include the most massive and largest galaxies discovered to date (Impey and Bothun 1997). For those LSBs that are disk systems (usually with masses comparable to late-type spirals), HI surveys have shown that they contain similar amounts of atomic material as their brighter (usually referred as High Surface Brightness, or HSB) counterparts in the Hubble sequence. This difference is mainly attributed to a much lower surface density in LSBs when compared to that of HSBs of similar size. In addition, their rotation curves tend to show a strong dark matter dominance, which suggests that the disks are usually resistant to star formation (Matthews et al. 2001). If star formation is inhibited in LSB disk objects then their low apparent surface brightness naturally follows, but more importantly this would suggest that their evolution would also proceed at a much *slower* pace than in HSB objects.

If the current scenario for the ISM evolution in these objects is correct, they constitute one of the best laboratories to test models of the effects of low metallicity in the physics of the ISM. The main objective of this project is to exploit the low metallicity environments in these objects to study the properties of two of the ISM components: the molecular gas and the dust. These components, when compared with those of HSBs, will provide an invaluable insight into the transformation of HI to molecular material at low metallicity, the effects of shear in molecular gas cloud formation, star formation inhibition and the validity of instability coefficients in LSBs, and low metallicity dust emissivity. Some of these goals will not only help researchers understand LSBs better, but can also be applied to objects early in the history of the Universe, when similar conditions may have been present.

Although these objects seem to have very low star formation rates, they are not entirely 'inert'. In fact, HII emission has been reported in several (Matthews et al. 1999). This indicates that at least to some extent the HI component has been transformed to molecular gas and therefore it should be detectable. Only one work so far seems to have been successful in detecting the molecular component in a small sample of objects (O'Neil et al. 2000). This work suggests a low molecular-to-atomic gas mass ratio for LSBs when compared with HSBs. The dust component, however, has proven more elusive. IRAS fluxes on nearby objects seem to indicate the presence of fairly warm dust (T~30K) and dust-to-gas mass ratios ten times lower than in HSBs. Also, some optical/NIR photometry seems to suggest the presence of highly clumpy dust concentrations in some objects while HSBs tend to have more continuous dust lanes.

At this stage of the research on the ISM conditions of LSBs, the main objectives are positive detections and study of the distributions of their components. As mentioned above, the atomic gas in the disk LSBs tends to have low column densities and dust may be quite clumpy, therefore the use of high-resolution observations in the pursuit of the elusive molecular and dust components is not a feasible option. On the contrary, at the moment the most important strategy is to try to select samples of disk LSBs that guarantee a high probability of success. For both the gas and dust components, clearly the best way is to increase the apparent line-of-sight column density, which requires high inclination objects. Vila-Vilaro has compiled a sample of twenty nearby high-inclination disk LSBs for this project from all the catalogues published thus far in the literature.

Since high-resolution is not required, the use of mm/sub-mm telescopes of intermediate size, with beams that will cover significant fractions of the targets without adding too much beam dilution is sufficient. The mm-wave line observing in this project (CO (1-0) and CO (2-1) in each target), requires very stable backends that can guarantee flat baselines for long integration times, because both lines will be quite weak. Furthermore, since most of the dust must be at very low temperatures, it requires good continuum mapping capabilities in the sub-mm, where most of the dust would radiate.

The combination of the SMT/KP12m telescopes is thus ideal for this project. The KP12m will be used for much of the early spectral line observations because of its good front-ends available at 3 mm and 1 mm, and for its very stable backends. Later, when the multiband (230/345 GHz) receiver is installed at the SMT and the first set of 512×1 MHz filters become available, the SMT will be ideally suited for the high frequency spectral line work. The continuum observations, of course, will be done at the SMT, where its excellent site combined with the power of its 19 channel 870 μm bolometer will prove quite useful in the course of this investigation.

III.1.3 Identifying the Warm Components of Nearby Galaxies

Several ongoing projects are currently being conducted at the SMT to examine warm gas in nearby galaxies via high-lying CO transitions. This work is often done in conjunction with CO: J=1→0 observations carried out at the KP12m. A primary motivation is to determine the extent of high temperature/high density material in these galaxies, and to establish regions of starburst activity, using CO line intensity ratios. Searches for CO, J=4→3 emission at 460 GHz have been initiated, for example, towards a sample of Seyfert galaxies. Thus far this line has been detected towards several objects, including NGC 5033 (Vila Vilaro et al., in preparation). Various types of galaxies have also been detected and mapped in the J=3→2 transition of CO (See Figure 7, section II). This study has demonstrated that the J=3→2 line can often be observed to the same extent as the J=2→1 and J=1→0 CO transitions, and that it is a better tracer of the nuclear regions and spiral arms than the lower excitation lines (Dumke et al. 2001). The new dual-channel single sideband 345 and 490 GHz receivers on the SMT will enable these investigations to be more time efficient and will improve the accuracy of the line intensity ratios.

III.2 Astrochemical Investigations

The ARO has prime instruments for the studies of interstellar and circumstellar chemistry because of its excellent frequency coverage and the use of dual channel single sideband receivers (a future plan on the SMT, but currently implemented on the KP12m). This research is complemented by the UA Spectroscopy Lab; it's major purpose is to measure rest frequencies of new and known (when needed) interstellar molecules. Among the projects to be done in the period of this grant are numerous searches for new interstellar species in particular those containing a refractory element (such as Si, Mg, Al, and Fe), as well as studies of large organic molecules related to astrobiology. Mapping of the detailed chemical structure of molecule clouds is also in progress especially for nitrogen containing molecules, (such as NO, N_2O, HNO^+, and HNO). Studies of interstellar and circumstellar isotope ratios are also planned in the future.

III.2.1 Broad-Band Spectral Line Identification of Large Molecules

There are several large organic molecules present in interstellar clouds that contribute a significant number of strong features to the mm/sub-mm spectrum. Representative of such species are methyl formate (CH_3OCHO) and dimethylether (CH_3OCH_3) and ethyl cyanide (CH_3CH_2CN). For example, over 175 transitions of methyl formate have been observed in the 215-265 GHz range alone towards OMC-1 (e.g. Blake et al. 1986). Over thirty lines are readily visible between 150-160 GHz (Ziurys and McGonagle 1993). These data were obtained with only moderate sensitivities of T_A^* ~0.03–0.1K; other transitions may be detectable with longer integration times. CH_3OCH_3 and CH_3CH_2CN are also quite prevalent in molecular clouds like Orion.

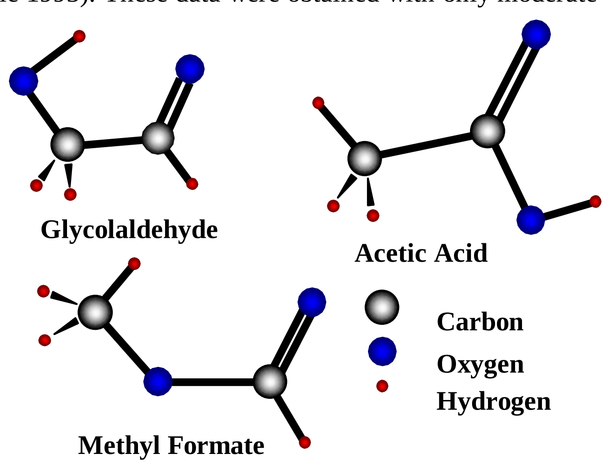


Figure 10. Chemical structures of isomers of methyl formate.

The preponderance of methyl formate in molecular clouds is a chemical curiosity. It does, however, suggest that the many unidentified lines found in mm/sub-mm spectra arise from large organic species. Because methyl formate is so abundant, it might be reasonable to expect that its geometric isomers might be present in molecular gas as well, such as acetic acid and glycolaldehyde, as shown in Figure 10. Searches for acetic acid have yielded a few possible lines observed towards SgrB2(N) (Mehringer et al. 1997). Given the frequent appearance of methyl formate features, these few coincidences for acetic acid makes this identification tentative, especially since both molecules have similar rotational energy level structures. In the case of glycolaldehyde, on the order of five features have been observed towards SgrB2(N), but there are "missing" transitions (Hollis et al. 2000). Again, the case for glycolaldehyde remains speculative.

Clearly if such molecules like acetic acid and glycolaldehyde are present in interstellar clouds, they should contribute a large number of spectral features both at millimeter and sub-mm wavelengths, especially at low noise levels. On the other hand, the details of the chemistry might not favor these isomers at all, and methyl formate may be the only carrier of this particular set of atoms. In any event, it would be extremely useful to definitively establish the existence of such large organics in molecular clouds and establish their rotational temperatures and abundances. Their contribution to the complete mm/sub-mm spectral flux could then be evaluated, and many U-lines might finally be identified. The U-line situation is somewhat intimidating at times, particularly towards sources like Orion and SgrB2. A recent example of this problem is illustrated in Figure 11, which shows a spectrum taken in January 2002, towards Orion-KL at 101.8 GHz, using the KP12m in a single side-band mode (an absolute necessity for weak line searches). Over a frequency range of less than 100 MHz, at least eight unidentified features are present. In fact, none of these lines in these data have been identified, despite searches through numerous line catalogs.

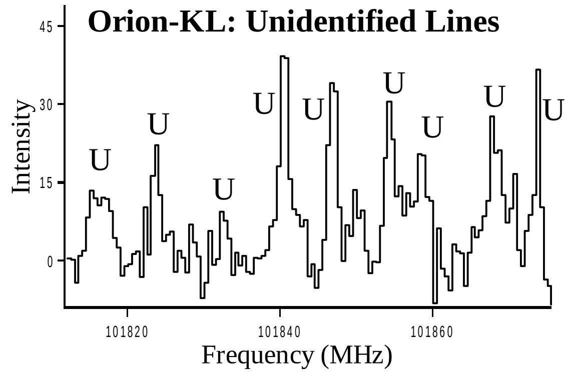


Figure 11. A spectrum observed with the 12m telescope towards Orion-KL, showing a host of unidentified lines.

As part of a 3-year observing program, the astrochemistry group at the UA proposes to establish the abundances and excitation of a group of large organic species whose identifications are tentative or have never been searched for, but likely exist. A list of candidate molecules is shown in Table 2. Laboratory data are available for some of these molecules, but additional lab measurements may be necessary. For two species listed, there are no known rest frequencies.

Table 2: Large Organic Molecules of Interest

Molecule	Chemical Formula	Laboratory Reference
acetic acid	CH_3COOH	Wlodarczak and Demaison 1988
glycolaldehyde	CH_2OHCHO	Butler et al. 2001
acetone	CH_3COCH_3	Groner et al. 2002
ethylene oxide	c-H_2COCH_2	Pan et al. 1998
1,2 Dihydroxyethylene	HCOH-CHOH	none
methylene glycol	$HOCH_2OH$	none

The strategy for this project is first to evaluate the currently available laboratory frequencies and establish a target list of strong transitions for these molecules that extends from 65 GHz upward into the sub-mm regions, perhaps as high as 800 GHz. With periodic scheduling at the two telescopes concerned, these transitions can be observed and a large database established. Some significant fraction of the proposed lines will likely be contaminated, but with broad spectral coverage, a sufficient number of "clean" transitions can be observed. From such a large data set, accurate rotational temperatures can be established, and hence intensity predictions can then be made into the THz regions for space-borne platforms such as SOFIA, Herschel, and SIRTF. When necessary, complementary laboratory measurements can be conducted in the Ziurys spectroscopy lab. The Ziurys/Apponi group has the necessary background to handle most spectroscopic problems. The target sources are Orion-KL, SgrB2(N), and W51, over the 3 year period.

III.2.2 Searches for New Circumstellar Molecules

To date, four metal cyanide species have been observed in the circumstellar envelopes surrounding late-type stars. MgNC, MgCN, NaCN, and AlNC have all been detected towards IRC+10216 (e.g. Ziurys et al. 2002), for example. In addition, MgNC and NaCN have been seen in the proto-planetary nebula CRL 2688 (Highberger et al. 2001) and MgNC in CRL618. These studies indicate that metal preferentially form cyanide complexes in circumstellar gas. Other such species may therefore be present in such objects.

Ziurys and co-investigators have begun a study of a new metal cyanide species using the KP12m, KCN. The high abundance of potassium chloride in IRC+10216 ($f_{(KCL/H2)}$ ~10^{-6}–10^{-8}, Cernicharo and Guélin 1987), and the prevalence of cyanide species makes KCN a likely candidate for molecular detection. In fact, five transitions of KCN in the range of 85 and 150 GHz have already been observed in IRC+10216 using the KP12m.

Figure 12 presents some of the currently detected features, including the $10_{0,10}\rightarrow9_{0,9}$ transition of KCN at 94.4 GHz and the $16_{0,16}\rightarrow15_{0,15}$ line at 150 GHz. Spectral resolution is 2 MHz. All KCN lines lie at the systematic velocity of the source, -26.0 km/s. KCN is an asymmetric top and has a complicated energy level pattern; therefore, additional transitions need to be detected before this identification can be confirmed.

Besides KCN, new searches will be conducted in the future for CaC, based on new laboratory measurements as well as NiCN and CrN. Observations of these and any other molecules found in the lab will be carried out during this grant period.

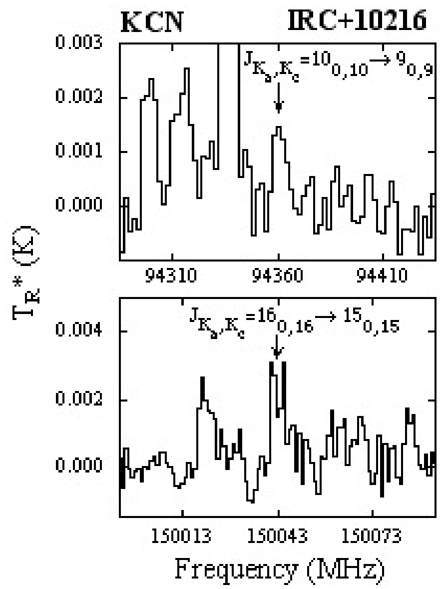


Figure 12. Spectra showing two possible transitions of KCN observed towards IRC+10216 with the KP12m.

III.2.3 Isotope Ratios from Interstellar CN

The $^{12}C/^{13}C$ isotope ratio in interstellar gas is thought to be a sensitive indicator of the degree of stellar nucleosynthesis and therefore galactic chemical evolution. Measurements of this isotope ratio have been carried out for many years across the Galaxy, using both radio and optical spectral measurements. In an ongoing effort to better establish $^{12}C/^{13}C$ ratios throughout the Galaxy, as well as understand the chemistry of isotopic fractionation, millimeter observations of another molecular tracer of this quantity, CN, have been conducted. Observations of CN and ^{13}CN at millimeter wavelengths enable accurate ratio calculations, since the rotational transitions observed show appreciable hyperfine splitting, enabling direct calculations of the opacity.

Past observations have included the N=1$\rightarrow$0 transitions of ^{12}CN and ^{13}CN ($X^2\Sigma^+$) at 113.5 and 108.8 GHz, respectively, which were observed in a sample of thirteen galactic molecular clouds using the KP12m. Hyperfine structure, arising from the nitrogen nuclear spin, was resolved in the spectra of both species, enabling an accurate determination of the opacity in ^{12}CN. From these measurements, estimates of the $^{12}C/^{13}C$ isotope ratio were obtained. These values fall in the range $^{12}C/^{13}C$ ~20-70 and exhibit a noticeable gradient with distance from the Galactic center (see Figure 13). In general, the ratios obtained from CN are very similar to those determined from millimeter observations of CO, but are consistently lower than those derived from H_2CO.

Analogous measurements are planned in the identical sample of molecular clouds, using the CN N= 2$\rightarrow$1 transition near 226 GHz and the N= 3$\rightarrow$2 line at 339 GHz at the SMT, as well as ^{13}CN in the equivalent lines. These observations will give two additional determinations of the $^{12}C/^{13}C$ ratio, as well as independent estimates of opacities in the CN lines. It may be that these higher lying lines are mostly optically thin, which eliminates the necessity of establishing opacities for isotope ratios. These measurements will be fundamental in establishing whether the carbon isotope ratio derived from CN is really distinct from that of H_2CO and will help determine the extent of chemical fractionation in this radical. These observations are also directly comparable to isotope ratios determined from cometary CN and thus can be used to establish chemical changes in the interstellar gas when the Sun formed 4.6 Gyrs ago.

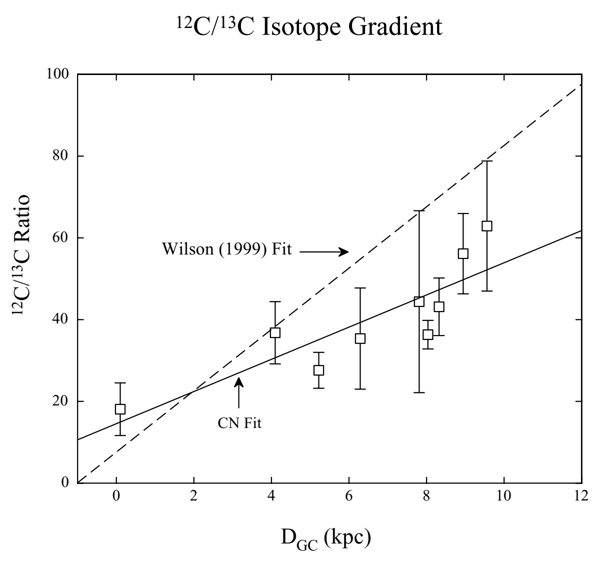


Figure 13. $^{12}C/^{13}C$ ratio plotted as a function of distance from the galactic center. The solid line shows the fit from the CN data and the dashed line that from Wilson (1999).

III.2.4 High Frequency Observing at the ARO

Another major thrust for the ARO is examining the limits of ground-based sub-mm (υ > 500 GHz) astronomy. Given the success of the THz, CO: J = 9→8 experiment, conducted in a window with a predicted 2-3% atmospheric transmittance, it is likely that many additional high frequency lines might be detectable, particularly in the 500-1000 GHz range. The priority observing scheduling at the SMT will be extremely advantageous for these high frequency measurements (see section V.3). Aside from the various transitions of CO and CS, the usual molecular cloud tracers, higher lying lines of molecular ions and hydride species are of interest, particularly the refractory hydrides. The molecular ions (HCO^+, N_2H^+ and isotopomers) are relevant because they have large dipole moments, and therefore their sub-mm lines will only be excited in very dense ($n \geq 10^7$ cm^{-3}) gas. Hydride species, in particular diatomic hydrides, are the fundamental building blocks of interstellar chemistry, and are predicted to be found in a variety of environments, including diffuse gas, shocked regions, and PDR's (e.g van Dishoeck 1995). Any hydride consisting of hydrogen combined with reasonably abundant element is important for the chemistry, as studies of HCl have demonstrated (Zmuidzinas et al. 1995; Salez et al. 1996). Of particular relevance are metal hydride ions with the simple formula MH^+. These species are directly formed from H_3^+ + M, or H_2 + M^+, hence they are the first products in the chain to neutral MH. At present, there is limited laboratory data concerning metal hydride ions, and none with the resolution required for astronomical searches. A separate laboratory program is currently being conducted to measure metal hydride ion frequency in the Ziurys group, funded by other sources. Nonetheless rest frequencies will become available for SMT searches. A list of proposed high frequency transitions is given in Table 3.

Table 3. High Frequency Molecular Transitions of Interest

Molecule	Transition	Frequency (GHz)
HCO^+	J = 7 → 6	624.3
	J = 9 → 8	802.7
	J = 10 → 9	891.9
N_2H^+	J = 7 → 6	652.2
	J = 9 → 8	838.5
	J = 10 → 9	931.7
SiH	J = 3/2 → 1/2	664.8
MnH	N = 2 → 1	672.2
AlH^+	N = 2 → 1	807.6
FeH^+	N = 2 → 1	679.2
NaH^+	J = 2 → 1	632.0

III.3 High Frequency VLBI Using SMT and KP12m

III.3.1 Introduction

The combination of SMT and KP12m sites in this proposed University Radio Observatory (URO) offers the astronomical community a unique and important opportunity in the field of mm wavelength Very Long Baseline Interferometry (mmVLBI). mmVLBI is the highest resolution technique available for astronomical study. At 3 mm wavelengths, VLBI can currently detect active galactic nuclei (AGN) with 80 μarcsec resolution, and at a wavelength of 1 mm, 25 μarcsec resolution is possible—only 1000 Schwarzschild radii of a 10^9 solar mass black hole at z=0.15. VLBI can also probe turbulent regions in envelopes of evolved stars and young stellar objects (YSO's) by imaging the compact (<1marcsec) molecular maser emission often found in these environments. A goal of this URO is to open new spectral windows for molecular studies and to increase angular resolution further by extending VLBI techniques to higher frequencies.

In April 2002, a collaboration of Haystack Observatory, Steward Observatory and the Max Planck Institute for Radio Astronomy successfully detected both 129 GHz and 147 GHz fringes on the SMT-KP12m baseline. Detections were made not only on the bright AGN, 3C279, but also on the SiO maser source, VYCMa making this the highest frequency spectral line VLBI to date. For a short time, the IRAM 30m telescope in Spain joined the array and the very long baselines to both Arizona sites also detected 3C279. With fringe spacings of slightly less than 50 μarcsec **these detections represent the highest angular resolution results ever achieved by any technique.**

This success underscores characteristics of the SMT-KP12m baseline that make it ideal as a testbed for technical development of mmVLBI. With a modest separation distance of ~160km, each site can share critical VLBI test equipment and personnel during setup for observations. Both sites are administered by the same organization, which greatly simplifies VLBI scheduling and logistics. It also allows for a convergence of VLBI hardware and software at both telescopes thereby reducing observing overhead, and makes possible some degree of dynamic scheduling. Lastly, both sites are frequency agile up to 300 GHz so that VLBI tests up to the sub-mm band can be explored. Such tests will lay the groundwork for large aperture mm wavelength antennas, arrays and prototypes (CARMA, LMT, ALMA, SMA) that will dramatically improve the sensitivity of future mmVLBI arrays and enable imaging of AGN at unprecedented resolutions.

In addition to technical advances, the VLBI with SMT and KP12m is poised to undertake several exciting mmVLBI scientific observations. The VYCMa SiO (J=3→2) detections, for example, indicate that maps of the maser emission can be made and compared to those of other SiO transitions to constrain maser pumping mechanisms and trace physical conditions in stellar envelopes. A second integral part of this proposal is to significantly increase the continuum VLBI sensitivity at both sites by using new Haystack-designed Mark5 VLBI recording terminals operating at up to 1Gb/s, a factor of 4.5 improvement over the April 2002 observations. With this enhancement, observations of SgrA*, the AGN at the center of our Galaxy, can be carried out on both short Arizona baselines and on long baselines to other antennas such as the SEST antenna in Chile and telescopes on Mauna Kea (JCMT and SMA). A simple VLBI detection on such long baselines would probe size scales of order 0.5 AU and immediately distinguish between several competing emission models for the massive black hole that resides in the galactic Center. Details of VLBI scientific goals, technical considerations and educational plans are given below.

III.3.2 Scientific Objectives

III.3.2.1 SiO Masers

Silicon Monoxide masers, excited by a combination of radiative and collisional pumps, arise in some atmospheres of both evolved stars and YSOs. Masers are observed in many ro-vibrational transitions of this simple rotor molecule, giving rise to very compact (0.1AU) and very bright (10^{13} K) features that trace long gain paths through stellar environments. VLBI has, in a real sense, revolutionized the study of this phenomenon. VLBI has done so by imaging complex maser structures with high spectral resolution, delivering detailed pictures of regions that are opaque in the optical and IR.

The Orion-BN/KL region hosts the archetypal SiO maser associated with a YSO. Within the nebula, Source I (Menten and Reid 1995) is a young massive star whose associated HII region lies at the exact centroid of the SiO masers. Early low-resolution single dish and mm-array work supported a model in which the masers formed in an expanding rotating disk (Barvainis 1984; Plambeck et al. 1990). New mmVLBI maps in three SiO transitions now show that the maser emission arises in four main emission regions arrayed along the arms of an "X" (Doeleman et al. 1999; Greenhill et al. 1998; Doeleman et al., in preparation) providing strong evidence for a bipolar conical outflow from this young star (Figure 14 a,b). Regional outflows seen in other molecules (CO, H_2, H_2O) also appear to originate near Source I and form a consistent picture in which the SiO masers trace the earliest stages of a molecular outflow that extends to much larger distances.

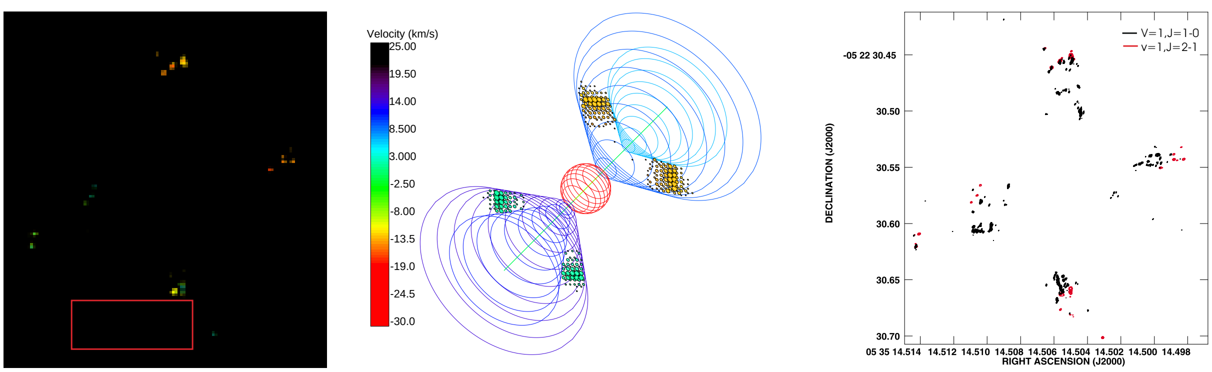
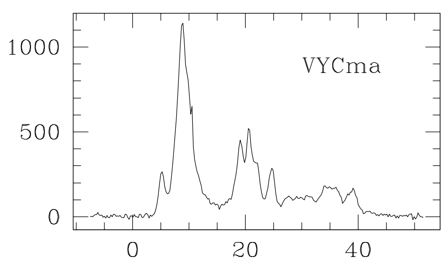


Figure 14. a) (left) A high resolution image of the 3 mm (v=1 J=2→1) transition made using an array of four antennas and color coded to reflect velocity (-10 km/s to 20 km/s). b) (middle) Numerical modeling of a bi-conical outflow which reproduces the four main emission regions seen in observations. c) (right) Comparison of the v=1 J=1→0 (43 GHz) and J=2→1 (86 GHz) lines showing the 3 mm masers to be generally located further from the central star than the 7 mm masers.

Contemporaneous VLBI images of three SiO transitions reveal that the bulk of emission from each maser line appears at different radii from the central protostar. Features in v=2 J=1→0 (42.8 GHz) form as close as 40 AU (projected distance) to the center, *v*=1 J=1→0 (43.1 GHz) occurs further out, and v=1 J=2→1 (86 GHz) is farthest with emission at projected radii up to 67 AU (Doeleman et al., in preparation). Theory predicts a spatial offset between J=1→0 transitions since the *v*=2 state requires an excitation temperature of 3600 K compared to only 1800 K for the *v*=1. The offset between the v=1 J=1→0 and v=1 J=2→1 emission (Figure 14 c), however, is surprising and breaks an expected link between the transitions predicted by both collisional and radiative excitation mechanisms. Some models (e.g. Lockett and Elitzur 1992) predict a dependence of relative maser gain in the two v=1 transitions on gas density. Thus, multi maser line imaging can reveal small-scale gradients in density and SiO abundances where the outflow impacts the surrounding clouds.

The SMT and KP12m antennas constitute the only VLBI baseline worldwide that can detect and image the $J=3\rightarrow2$ (129 GHz), $J=4\rightarrow3$ (172 GHz) and $J=5\rightarrow4$ (215 GHz) SiO maser transitions with angular resolution comparable to known maser structures. Given the newly discovered spatial offsets between lower frequency maser lines, VLBI exploration of SiO masers in the 1-2 mm band will reveal unforeseen relationships among the maser transitions. As maser models become further refined (at this point primarily through VLBI observations), the efficacy of masers as useful probes of their environments will grow. In the model of Doel et al. (1995), for example, the ratio of $J=2\rightarrow1$ and $J=1\rightarrow0$ intensities is closely related to the gas density, but the effects of competitive gain if the masers are saturated can modify this dependence. Comparison of $J=5\rightarrow4$, $J=4\rightarrow3$, and $J=3\rightarrow2$ maser features with the lower frequency emission can, within the context of this model, be used to estimate saturation levels and thereby refine density predictions.

Orion-KL is but one example of how SiO maser imaging is fundamentally changing our views of the dynamics and physical conditions of stellar environments. Mass-loss envelopes of Red Giant stars such as R Cassiopeiae can also be studied with multi-transition SiO maser VLBI (Phillips et al. 2001). In contrast to Orion-KL, R Cas shows the v=1 43 GHz and 86 GHz masers to be largely co-spatial, and pulsating shocks from the central star may dominate the excitation of both transitions (Humphreys et al. 2002). In addition to SiO masers, the SMT-KP12m baseline will be able to make the first VLBI detections of proposed masers in HCN (177 GHz), methanol (157 GHz), hydrogen recombination lines (147 GHz and 231 GHz), and water (183 GHz) to confirm their compactness (Lucas and Cernicharo 1989; Slysh et al. 1995).



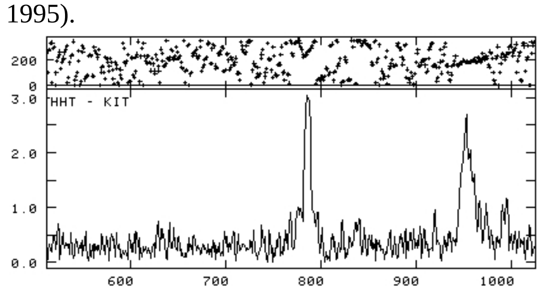


Figure 15. a) (left) Spectra of the SiO v=1 $J=3\rightarrow2$ (129.36 GHz) maser transition in VYCMa with the KP12m on 26 September 1999. Spectrum is calibrated in Jy and velocity is VLSR in km/s. b) (right) VLBI cross power spectrum of VYCMa in April 2002. Phases are in top panel and correlation amplitudes in bottom panel.

On the SMT-KP12m baseline, the 129 GHz detection threshold in 10 seconds for a typical 62.5 kHz channel with 2-bit per sample recording is 150 Jy. Due to strong variability, ~5 objects out of a total of ~25 historically bright SiO maser sources, will exceed this limit during any given observing epoch (e.g. Figure 15a). Figure 15b shows the VLBI cross power spectrum of the evolved star VYCMa taken during the April 2002 VLBI observations. The differing interferometric phases of the two main emission peaks implies that the peaks correspond to spatially distinct maser features around the star. Maser mapping using a single baseline is well understood (Doeleman et al. 1998) and these techniques will be used to image SMT-KP12m data on the brightest SiO maser sources.

*III.3.2.2 The Galactic Center: SgrA**

The case for linking the compact radio source SgrA* with emission from a 2.5×10^6 solar mass black hole at the center of the Galaxy is now quite strong. High velocity dispersions (~1400 km/s) of stars near the Galactic center (Eckart and Genzel 1997; Ghez et al. 1998), observed accelerations of these same stars (Ghez et al. 2000), and upper limits on the proper motion of Sgr A* itself (Backer and Sramek 1999; Reid et al. 1999) all point towards this conclusion. Perhaps the greatest mystery surrounding this uniquely nearby AGN is that it radiates at 10^{-8} of the Eddington limit, despite abundant gas in the Galactic Center that could fuel a much larger luminosity (Quataert et al. 1999). Directly measuring the intrinsic size of Sgr A* is of fundamental importance in constraining proposed emission models of the central black hole, and high frequency VLBI provides the only means available to do so.

From 18 cm to 1.3 cm wavelengths, VLBI images of Sgr A* are distorted by an ionized scattering screen which broadens the image into an ellipse of axial ratio 0.5 with axes scaling as λ^2 (Jauncey et al. 1989; Marcaide et al. 1992; Alberdi et al. 1993). Using 7 mm wavelength VLBI, Lo et al. (1998) report a departure from this axial ratio which would be compelling evidence for North-South intrinsic structure in Sgr A*. 3 mm-VLBI, which is much less affected by scattering, detected Sgr A* (Doeleman et al. 2001) using a six station array (KP12m, OVRO, BIMA, VLBA sites at PieTown, Los Alamos, Fort Davis) and used calibration independent closure quantities to model the Sgr A* structure. These 3 mm data are best fit by a circular Gaussian structure of full-width half-maximum 0.18 ± 0.02 mas in apparent disagreement with the elongated structure seen at 7 mm. The 3 mm results are consistent with the scattering size of an unresolved source: the intrinsic nature of Sgr A* has, so far, eluded our best efforts. One group of emission models known as Advection Dominated Accretion Flows (ADAFs) have been ruled out by these 3 mm VLBI observations. ADAFs account for the low luminosity of Sgr A* by assuming that hot infalling plasma crosses the black hole event horizon before radiatively cooling, but predict an emission region size that far exceeds mmVLBI upper limits (Özel et al. 2000).

The most promising avenue for further progress in understanding the nature of Sgr A* is to pursue high frequency VLBI where the scattering size falls below the angular resolution. The SMT and KP12m antennas will be integral parts of arrays that attempt to detect Sgr A*, making use of MK5 VLBI recorders to more than double current sensitivities. At 230 GHz, the scattering ellipse of Sgr A* will measure 24 × 13 μarcsec (minor axis oriented NS) and Sgr A*, with a positive spectral index of ~0.3, will have an average flux density of ~2.5 Jy. Baselines from KP12m/SMT to the SEST telescope in Chile will have fringe spacings of 38 μarcsec and be able to detect sources down to a flux density of 1.4 Jy. On baselines from Arizona to the JCMT in Hawaii, the fringe spacing is 62 μarcsec with similar sensitivity. A detection on any of these baselines at 230 GHz would firmly limit the intrinsic size of Sgr A* to be of order one half the fringe spacing, or 3-5 Schwarzschild radii of the central black hole. This size scale is particularly important as it closely matches the x-ray emission region size inferred from the recent detection of a Sgr A* flare (Baganoff et al. 2001). A VLBI detection in combination with the x-ray size would strongly implicate a Synchrotron Self Compton emission mechanism for the x-ray flux, a process in which relativistic electrons can up-scatter radio photons to the x-ray band in very compact regions (Liu and Melia 2001). Future mmVLBI arrays including large telescopes will lead to detailed images of Sgr A* on 0.5 AU linear scales (Figure 16).

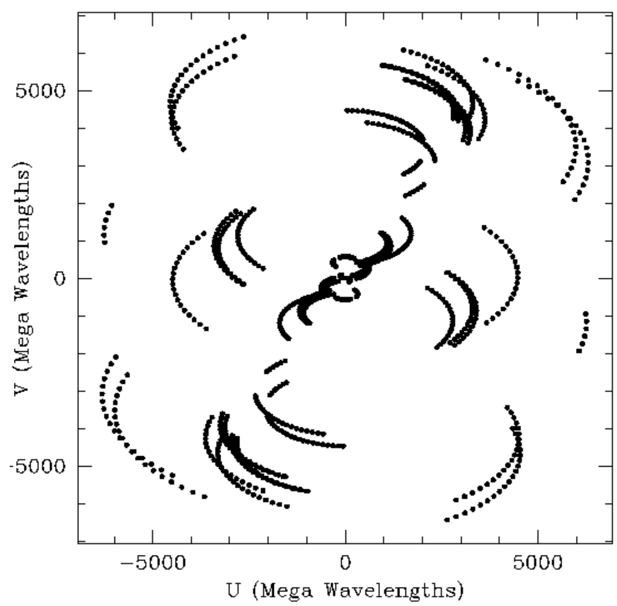


Figure 16: VLBI baseline coverage possible using an array including: ALMA, CARMA, SEST, KP12m, SMT, IRAM 30m, JCMT at a frequency of 230 GHz.

Technically, the SMT-KP12m baseline will serve as a primary test bed for building on the 129/147 GHz success and moving to 230 GHz and 300 GHz. Tests at 230 GHz will also include the BIMA site (prior to its integration into CARMA in 2004) which has been supported for VLBI with help from CMVA. A first step towards long baseline 230 GHz detections will be positive results on a moderate size 230 GHz array in the southwest US.

III.3.3 Technical Challenges and Requirements

The primary technical goals of this proposal are centered on enhancements at both SMT and KP12m for continued 2 mm VLBI and extension to higher frequencies. Reduction of phase noise in Local Oscillator (LO) electronics is the critical concern, and testing prior to the VLBI in April 2002 revealed several areas that require improvement. New ultra low noise 5 MHz references will be purchased and used in clean-up loops on the hydrogen maser outputs to reduce high frequency noise (>50 kHz) that has been traced back to the current references. Two new cavity tuned oscillators in the 7-9 GHz range will serve both as low noise test sources and later as microwave references for a low noise 230 GHz LO at both sites. Procurement of a new high-resolution spectrum analyzer will replace a critical piece of test equipment used to measure phase noise that was borrowed from NRAO for the April 2002 tests.

Improvements to the VLBI systems are focused on enabling 1Gb/s recording using the new MK5 VLBI recording system in development at Haystack. Two MK5 units will be constructed and tested at Haystack, then shipped to SMT and KP12m. The high frequency VLBI project will be able to draw on the experience and expertise of Haystack personnel for MK5 integration. For the April tests several components of the VLBI systems were on loan and replacements will be necessary for future work. The nine Base Band Converter (BBC) units used at the SMT and KP12m will come from upgrading older versions to incorporate both 8 MHz and 16 MHz filters enabling high bit rate recording. Haystack has a surplus of the old units and costs for new BBCs reflect only new parts and labor. In addition, two new VLBI field system computers will be purchased to replace previously borrowed equipment.

Based on discussions with the SMA group, a hydrogen maser and VLBI system for use by the JCMT, SMA and the CSO will be acquired by the SMA in the next two years; optical fiber linking all three telescopes has already been laid. BIMA is part of the current 3 mm-VLBI network and will purchase a MK5 recorder.

III.4 The Late Stages of Stellar Evolution

The SMT and KP12m have made and will continue to make significant studies of circumstellar gas and dust from post-main sequence stars. Mass loss is a critical factor in the evolution of intermediate mass (~1-8 M_{Sun}) stars, from red giant to planetary nebula/white dwarf. The ejected matter is a main source of replenishment for ISM, including enrichment in certain elements such as carbon and s-process nuclei. Mass loss from cool stars, especially Asymptotic Giant Branch (AGB) stars, is probably the dominant source of refractory interstellar dust grains (both silicate and carbonaceous types). For high mass stars (>10 M_{Sun}), mass loss is an important part of post-main sequence (MS) evolution during the red supergiant phase in the stages leading to a supernova. During the proposed grant period, ARO will initiate or continue studies in several key area.

III.4.1 Circumstellar Chemical Processes: Shocks and Refractory Molecules

Shocks: In a study of molecular envelopes of AGB stars with the SMT, Bieging et al. (2000) found strong evidence that non-equilibrium processes, probably pulsation-driven shocks, are responsible for the high observed abundances of HCN in oxygen-rich (M-type) stars and of SiO in carbon stars. Equilibrium chemical models are incompatible with these abundance patterns. The very strong sub-mm lines of HCN and SiO that Bieging et al. detected with the SMT, require that the non-equilibrium species are formed close to the stellar photosphere to explain the high excitation temperatures. Observations of the higher-energy molecular lines accessible in the sub-mm are critical to testing possible models, e.g., pulsational shocks in the stellar atmosphere vs. photochemical processes driven by ambient UV light in the outer envelope.

Bieging and colleagues will follow up the provocative results of the previous SMT study by (i) using both the SMT and KP12m to observe HCN and SiO in a wide range of excitation levels, for a larger sample of AGB stars; and (ii) observe additional molecular species, including CS and SiS, which shock-chemistry models of AGB star winds find to be enhanced in abundance by shocks (Willacy and Cherchneff 1998; Duari et al. 1999). New studies will provide a critical test of the hypothesis that AGB star winds bear the chemical imprint of strong shocks due to stellar pulsations. The pulsations may also be the mechanism initiating the high mass loss rates found in this important phase of stellar evolution.

Refractory Molecules: The detection of many metal-bearing molecules in the carbon-rich, circumstellar envelope of IRC+10216 clearly indicates that not all refractory elements are condensed into dust grains. The most recent identifications (MgNC: Kawaguchi et al. 1993, MgCN: Ziurys et al. 1995, and AlNC: Ziurys et al. 2002) are of molecules that apparently arise from the outer envelope of IRC+10216, in relatively cold gas (~25 K) where grain formation has ceased.

Other objects besides IRC+10216 clearly need to be investigated for the existence of refractory species: Ziurys and cooworkers have begun a systematic survey of carbon-rich circumstellar envelopes to identify metal-bearing molecules in these objects. Thus far, they have found AlF, NaCN, NaCl, and MgNC towards the post-AGB object CRL2688, and MgNC in the proto-planetary nebula CRL618, primarily using the KP12m. Abundances of species like MgNC and AlF are quite high and at least match those of IRC+10216 (Highberger et al. 2001). Several of these molecules have been tentatively observed in other carbon-rich shells, but await confirmation. It is quite interesting that these refractory species are still in detectable quantities in the proto-planetary nebula stage. Such observations suggest that a significant fraction of refractory material may remain in the gas phase as it enters the interstellar medium. A statistical sample of AGB and post-AGB objects needs to be investigated to clarify this aspect of stellar mass loss. The KP12m at 3 mm/2 mm is the preferred instrument, especially with its extremely stable, single sideband receivers.

III.4.2 Sub-mm emission lines of CO: Mass Loss Variations and Thermal Processes

The CO molecule is the best tracer of gaseous mass loss from cool evolved stars, and its lowest two rotational lines ($J=1\rightarrow0$ and $2\rightarrow1$) have been used to estimate total gas mass loss rates for a few hundred AGB and other cool giants, typically with the model formula of Knapp and Morris (1985) and subsequent refinements (e.g., Kastner 1992). The sub-mm CO transitions observable from telescopes such as the SMT, including the $J=3\rightarrow2$, $4\rightarrow3$, $6\rightarrow5$, and $7\rightarrow6$ lines, have been relatively little used to explore post-MS stellar mass loss. Studies of a small number of AGB stars, such as IRC+10216 (Groenewegen et al. 1998, Schoier 2000) and V Cyg (Bieging and Wilson 2001) have revealed important trends implying significant departures from assumptions (constant spherical mass loss, simple radial temperature law) made in the canonical picture of Knapp and Morris. Bieging and Wilson found that models of CO emission for the carbon star V Cyg fit all the multi-transition CO data if a secular decrease in mass loss rate is invoked, and if there is a significant heat input in the outer circumstellar envelope, probably via the photoelectric effect on circumstellar grains. The important point is that accurately calibrated observations of a wide range of CO line excitation levels are critical to test detailed physical models for the circumstellar matter. The SMT with its stable pointing and surface, together with improved SSB operation for the facility receivers (see Proposed Technical Developments, section IV) will allow ARO to obtain spectra of higher-excitation CO lines with precision calibration for a large, representative sample of red giant stars. These data will be compared with a new suite of physical models like those applied by Bieging and Wilson to V Cyg, to examine systematically the range of physical conditions in AGB star envelopes.

III.4.3 Thermal emission from circumstellar dust

Though AGB stars are believed to supply the largest part of refractory interstellar grains, more precise values for this important recycling process could be determined by new and better data on the sub-mm grain emission. With the 19-element array, ARO can make accurate, sensitive maps of thermal emission for the full extent of the dust envelope. The capability of the array to remove atmospheric fluctuations with rapid beam chopping on the SMT and the intrinsic sensitivity of the detectors should allow for the accurate measurement of the total flux and spatial distribution of the dust in a large and representative sample of relatively nearby (<1 kpc) AGB and post-AGB stars.

By combining such photometric data with that available from the IRAS catalogs, ISO photometric images (where available) and with new data that will be obtained from the imaging far-IR photometer (MIPS) on SIRTF, ARO will construct spectral energy distributions (SEDs) for the dust emission. Model fits to the SEDs may reveal systematic differences among spectral types (M, S, and C-type AGB stars) for example, related to the very different chemical abundances and dust compositions (silicate vs. graphite, amorphous carbon, or metal carbides). Modeling the dust emission will also yield dust mass loss rates (e.g., van der Veen et al. 1995). Mapping the extended dust emission for the nearest and highest-mass loss rate stars will give information on the spatial distribution of the ejected matter, and on variations in mass loss rate over time. The excellent image fidelity that can be achieved with the 19-element array will be critical in this respect.

A related class of mass-losing stars worth further study are the red supergiants (RSGs). Although far-IR "debris shells" with sizes of up to a few arcmin were recognized around such stars from IRAS (Stencel et al. 1989) and dust loss rates derived from IR photometry (Josselin et al. 2000), relatively little has been done to use sub-mm emission to determine the extent and nature of the ejected dust grains. The dramatic images of the rings around SN 1987A illustrate the importance of mass loss in the RSG phase preceding a SN, so further studies of such stars with the 19-channel bolometer on the SMT will help illuminate this stage of massive star evolution.

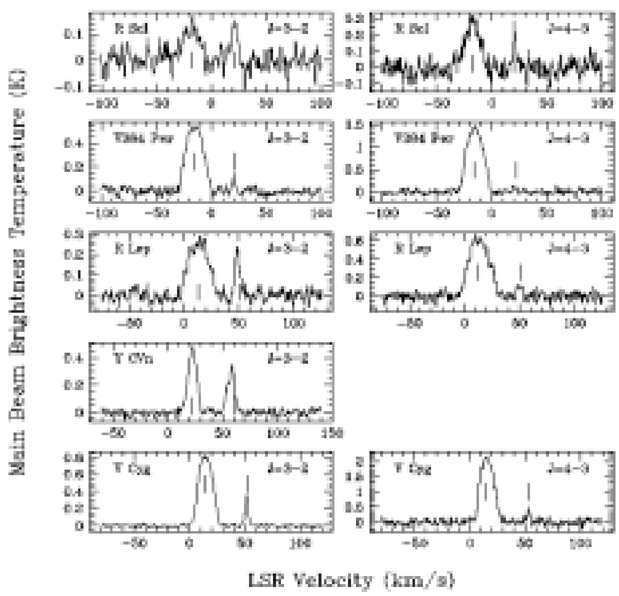


Figure 17. SMT spectra of HCN $J=3\rightarrow2$ and $4\rightarrow3$ transitions for carbon stars showing maser emission in the $(01^{1c}0)$ vibrational state. The vertical lines shows the relative spacing of the ground vibrational state transition (left) and the vibrational state (right).

III.4.4 Circumstellar masers

In a survey with the SMT of HCN and SiO emission from AGB star envelopes, Bieging (2001) reported the serendipitous discovery of maser emission in $(01^{1c}0)$ $J=3\rightarrow2$ and $4\rightarrow3$ vibrationally excited lines of HCN. These transitions were not previously known to be masers, but five out of twelve carbon stars showed clear evidence for maser action in lines at 267 and 355 GHz (see Figure 17). With evidence for variability, it is likely that most carbon stars show maser action in these HCN lines at least some of the time. This discovery is significant because almost all previously known maser emission lines, in OH, H_2O, and SiO, are found only in M-giants and supergiants, not in carbon stars, which have a very different chemical makeup. Like the SiO masers in M-giants, the HCN masers almost certainly arise in the inner envelope, close to the zone of wind acceleration, and as for the SiO masers, offer a way of probing the dynamics and physical conditions in this very interesting but otherwise nearly inaccessible part of the stellar envelope. These HCN studies are synergistic with VLBI measurements of SiO masers in late-type stars.

These masers arise from only one of several HCN vibrational modes. An obvious question is, what is the maser pump mechanism, and do other modes also show maser action? As part of the stellar envelope program for the proposed grant period, Bieging will pursue a systematic investigation of the carbon star/HCN maser phenomenon. A larger sample of stars, with a range of mass loss rates and IR colors will be surveyed for HCN masers, to look for systematic trends with stellar properties. Stars with detected masers will be observed in the other vibrational modes of HCN to see if these modes support inverted populations as well. With constraints on the pump mechanism, and velocity information from the maser spectra, the physical conditions in the zone of wind acceleration where mass loss arises should be determinable.

III.5 Galactic Structure and Star Formation

III.5.1 A Sub-Arcminute 'Most-of-the-Sky' CO Survey

It is remarkable that three decades after the discovery of CO, no definitive, comprehensive survey of Galactic CO emission exists. The best existing surveys of molecular gas were obtained with large beams (e.g. > 9' Dame et al. 1987, 2001), under-sampled (e.g. the 3' sampling of the UMass/Stonybrook survey-Solomon et al. 1987; Scoville et al. 1987), have limited areal coverage (e.g. Carpenter et al. 1995; Clemens 2001; The Bell Labs surveys-Stark and Brand 1989; Bally, et al. 1987b, 1988; 1991; Miesch and Bally 1994). Furthermore, these surveys utilized the $J = 1 \to 0$ rotational transitions of CO; the column density derived from optically thin (isotopic) $J = 1 \to 0$ emission is sensitive to the assumed (and often poorly determined) excitation temperature.

Molecular clouds still pose a host of questions regarding their nature and role in the coupling of matter in the ISM. How do molecular clouds form and evolve? How does star formation start and propagate through these clouds? What are the mass-spectra and kinematic properties of the clouds and the substructures that they contain? How do cloud properties change across the Galaxy? How do radiation (especially from massive stars) and outflows affect cloud structure? What are the relative roles of super-bubbles and local gravitational instabilities in the ISM swept-up by these bubbles, global instabilities of the Galactic disk, spiral density waves, and infall from above and below the plane in forming and/or destroying molecular clouds? What factors determine the stellar initial mass function, multiplicity, and clustering properties?

Answers to these questions require a new CO survey that provides higher angular resolution (<30″), and sufficiently discriminates diagnostics of temperature and density to detect the dense and heated interface regions between HII regions and adjacent clouds. This is not possible with lower resolution data since these gradients and enhancements will be washed-out (beam-diluted). To resolve a feature such as the Orion warm ridge in the Molecular Ring (d ~5 kpc) requires better than 1′ angular resolution.

The new multi-feed receivers, on-the-fly (OTF) mapping, and inexpensive computer hardware makes it possible to map the known regions with CO emission with better than 30" angular resolution. The SMT and KP12m radio telescopes in Arizona are ideal for such a survey in the $J = 2 \to 1$ and $J = 3 \to 2$ ^{12}CO, ^{13}CO, and where needed, $C^{18}O$. A team led by J. Bally (Colorado) intends to conduct such a survey using the ARO telescopes. This survey will have a mass sensitivity (to pre-stellar cloud cores) well below the brown-dwarf mass limit at d < 1 kpc, to < 1 M_{Sun} at 4 kpc for optically thin ^{13}CO $J = 2 \to 1$ emission, and 1 M_{Sun} throughout the Galaxy for optically thin ^{12}CO $J = 2 \to 1$ emission. Tens of thousands of pre-star forming cores will be identified. The < 30″ angular resolution is about 6 to 18 times better (36 to 300 times in area) than previous large-scale surveys (SUNY/UMass; 3′ grid; CfA/Columbia/CTIO; 9′ beam). The survey will produce a uniform (in sampling and sensitivity) large-scale data cube of the cold and dense molecular phase of the ISM in our Milky Way. This survey will be as fundamental to the investigation of the cold ISM as the IRAS survey is to the study of warm dust, and the Palomar Sky Survey is to the study of the visual wavelength sky.

III.5.1.1 Scientific Objectives of the Survey

The Nearby "Ecology" of the ISM and the Evolution of GMCs: The nearest star-forming complexes provide the best opportunity to obtain a comprehensive and complete view of star formation. This "solar vicinity" contains three major OB associations still forming stars (Sco-Cen, Perseus OB2, and Orion), about a dozen smaller complexes such as Taurus which form only low-mass stars, and a half-dozen giant molecular clouds (mostly associated with active star-forming regions). These star-forming complexes have enormous angular extents; the Taurus dark clouds cover more than 10° by 20° (Matsunaga et al. 2001), and Orion's two GMCs, cover over 20 square degrees (Maddalena et al. 1986; Bally et al. 1987a; Dame et al. 2001). Existing data are mostly in $J = 1 \rightarrow 0$ CO, and have insufficient resolution to isolate individual star forming cores. The higher-J lines of ^{12}CO, ^{13}CO, and $C^{18}O$ can provide better resolution, temperature, column density, and density diagnostics. This survey will trace the impact of young (1 to 15 Myr old) and forming stars on clouds. The multi-transition database will measure the heating, acceleration, and destruction of clouds by radiation and outflow activity. The new survey will provide definitive constraints on the evolution of clouds and the history of star formation in the Solar vicinity within the past 15 Myr.

The Origin, Evolution, and Destruction of Molecular Clouds: The spatial and velocity relationships between molecular clouds on the one hand, and groups of nearby stars (individual stars associations, or clusters with known ages), HII regions, super-shells, and atomic (HI) clouds on the other, provide key observational diagnostics of cloud formation, evolution, and destruction.

Elmegreen (1982), Olano (1982; 2001), and Bally (2001) propose that molecular GMCs form from the gravitational fragmentation of super-shells, energized by massive stars spawned by progenitor OB associations. The CO survey will provide a direct test of this model by tracing the Galactic longitude dependence of the radial velocity field of all nearby CO clouds, by searching for second-generation molecular clouds which may have formed from "super-rings" surrounding moderate age (less than 100 Myr old) clusters in the Galactic plane, and by directly searching for younger molecular supershells and 'super-rings' associated with still active OB associations.

Other models of cloud formation propose that GMCs form from spiral density shocks, or global instabilities of the disk (Lin and Shu 1964; Jog and Solomon 1984ab; Wada and Norman 2001). The former model predicts that near the tangent points of spiral arms, there ought to be a clear correlation of age with distance from the spiral shock. The latter model predicts that GMCs are parts of 'superclouds' with 1 kpc dimensions. On-going IR surveys will enable the age-dating of young stellar associations in distant parts of the Galactic plane where these models can be tested. The proposed survey is required to link individual clouds to these stellar associations so that stellar ages can be transferred to the clouds.

Large-Scale Structure of the Galaxy: The proposed survey will provide the best determinations of the rotation curve of the Galaxy (from radial velocity at the tangent point; e.g. Clemens 1985), cloud-to-cloud velocity dispersion (from fluctuations of the radial velocity at the tangent point), the CO scale-height, and the dependence of these parameters on Galacto-centric radius and location with respect to the spiral arms. (e.g. Liszt and Burton 1981; Stark 1984; Blitz et al. 1984; Stark and Brand 1989). Association of young star groups (using 2MASS, MSX, the upcoming SIRTF Galactic Plane survey, and new NIR cameras) with specific CO clouds will link molecular cloud temperature gradients and density enhancements to specific stars, HII regions, and ionization fronts, and lead to much better determination of the distribution of GMCs in the Galaxy. "Peculiar velocities" will identify mass concentrations associated with the central bar (Binney et al. 1991), the spiral arms, and other kpc-scale galactic structures. The proposed high-J survey will be vastly more sensitive than J=1-0 maps to the distribution and kinematics of molecular gas away from the Galactic midplane and to translucent molecular clouds. These data will be used to study the kinematics and dynamics of high-latitude clouds and the contribution of diffuse molecular clouds to the CO luminosity of the Milky Way. Do these clouds trace the "galactic fountain" of material launched to high-z by super-bubbles? Do they trace infalling material condensing from halo gas?

Properties of Molecular Clouds, Star Forming Regions, and Individual Cores: Previous CO surveys of the Galactic plane all suffer from confusion produced by unrelated clouds superimposed along the line-of-sight (Liszt and Burton 1981; Liszt et al. 1981). Simulated observations show that blending of emission from physically unassociated objects leads to the "detection" of spurious giant molecular clouds and greatly alters the apparent size and mass spectra from the actual distributions. The survey will be used to identify thousands of cloud cores and clumps. The unprecedented resolution, sample size, and the multi-transition data, will lead to a robust determination of their masses sizes, column densities, internal velocity dispersions, and angular momentum distributions. The $J=3 \rightarrow 2$ transition is crucial for constraining temperatures and densities; these lines, originating 33 K above ground, are most sensitive to warm gas surrounding stars, photo-heated cloud surfaces, and to the cooling and/or molecular re-formation layers behind shocks. Thus, the $J=3 \rightarrow 2$ lines will provide the best probes of cloud acceleration / disruption by stars, photo-dissociation regions, and supersonic flows.

Outflows: Outflows from young stars can regulate the overall gravitational collapse of molecular clouds, impact their evolution, alter their structure, and through shocks, alter the chemical state of the gas. This project will identify hundreds of molecular outflows in CO, providing very large unbiased samples, enabling the determination of their total energy and momentum input into the host clouds, and the dependence of outflow properties on YSO age, environment, and other factors.

III.5.1.2 The Proposed Survey

A seven-beam array receiver at 345 GHz will be available on the SMT, and a dual-polarization single-beam receiver at 230 GHz on the KP12m. When combined with the "on-the-fly" (OTF) mapping technique, these two telescopes provide an unprecedented improvement in mapping speed. The survey will be in the J = 2→1 and J = 3→2 CO lines, resulting in higher spatial resolution (beam FWHM ≈ 30"). For optically thick J = 2→1 lines, the derived column density is insensitive to variation in excitation temperature. The column density of thin J = 2→1 lines is given by

$$N({}^{x}C^{y}O) \approx \frac{1.3\text{x}10^{14}(T_{ex}+0.9)\exp[10.6/2T_{ex}]}{T_{ex}(1-\exp[-10.6/T_{ex}])} I({}^{x}C^{y}O)$$

where T_{ex} is the excitation temperature, *x* and *y* refer to the isotopic variant of CO, and *I*(CO) is the velocity integrated CO intensity in the beam (in K km s^{-1}). For T_{ex} = 10 to 30 K, N(C O)/I(${}^{x}C^{x}$ O) ranges only from 3.3×10^{14} cm^{-2} to 5.0×10^{14} cm^{-2} (corresponding to molecular hydrogen column densities of 2.3 x 10^{20} cm^{-2} and 3.5×10^{20} cm^{-2} for ^{13}CO and a ^{13}CO abundance of $N(H_2)/N(^{13}CO) = 7 \times 10^5$). For a 30″ diameter beam, the mass sensitivity is given by $M = 7.5{\times}10^{-2}\, d^2_{kpc}\, I(^{13}CO)\, M_o$ where d_{kpc} is the distance to the region under study in kpc. ARO will remap areas where CO saturates in ^{13}CO and/or C^{18}O. This nested grid strategy will make it possible to get good estimates of the gas column density over a very broad range of physical conditions. Our nominal sensitivity for a fiducial system temperature (including the atmosphere) of $T_{sys} = 10^3 T_3$ K is given by $T_{rms} = 1.4 T_3\, t_{sec}^{-0.5}\, \Delta\nu_6^{-0.5}$ K, where $\Delta\nu_6$ is the frequency width per channel in units of 1 MHz and T_3 is the total system temperature in units of 10^3 K. A one second integration achieves a sensitivity of roughly 0.7 K in 1 km s^{-1} channels, for expected values of T_3 = 0.3 – 0.5 at 230 GHz and T_3 = 0.5 at 345 GHz.

ARO will sample the sky on a uniform 15″ grid, so there are 16 independent spectra per square arc minute. This requires that 57,600 independent spectra be obtained per square degree after combining multiple OTF rasters into individual (level-0) spectra. With 7 beams and 1s effective integration time per spectrum, it will take about 7200 seconds (2 hours) to map each square degree. Since a full beam size of 30″ contains about 4 independent spectra, the full resolution survey will have a sensitivity of nearly 0.5 K in 1 km s^{-1} channels. Typical giant molecular clouds such as Orion A have J = 2→1 peak temperatures ranging from 10 to 100 K in ^{12}CO and 2 to 30 K in ^{13}CO. Line widths range from about 1 km s^{-1} to over 10 km s^{-1}. This survey will have sufficient sensitivity to detect and image all known types of clouds.

Assuming that each receiver uses a 256 channel spectrometer, and that each channel is stored as a 2 byte integer, the total data storage requirement is 2.3×10^8 bytes per square degree (0.23 Gbyte deg^{-2}). At the above effective integration time, the survey can cover about 12 square degrees per day, or 2.8 Gbytes per day (~700,000 spectra per day). This survey will go into the public domain immediately after reduction (no proprietary period for the team).

This study will systematically survey the entire portion of the Milky Way visible from Arizona. Approximately 500 square degrees of sky will be covered and fully sampled with OTF. This corresponds to a time requirement of about 2000 hours of observing time or 84 clear days. This part of the survey will sample the full range of conditions encountered in the Galaxy, including the Galactic center, the molecular ring, the outer Galaxy, nearby and distant molecular clouds and star-forming regions, and distant high latitude clouds. The backbone of the survey will be conducted in the J = 2→1 and 3→2 ^{12}CO lines. Regions where the opacity is deemed to be high (based on a predetermined brightness criterion) will be resurveyed in ^{13}CO and even in C^{18}O. Some of the Galaxy will have to be covered in all three CO isotopes to insure that at least one transition is optically thin, and can be used for reliable column density derivations. ARO will obtain fully-sampled mapping of well known off-plane cloud complexes, such as Orion, Perseus, Taurus, ρ Ophiucus, and Cepheus, which were initially discovered in the Columbia/CfA surveys. This survey will cover much of the sky where CO is known to exist (a few percent of the sky). The total number of spectra will be around 10^8 requiring less than 1 Tbyte of storage.

Data Acquisition and Reduction Plan: The raw-data (level-0 data product) will be retained on archival DVD files for processing and re-processing if needed. The NRAO AIPS-based system will be used to process raw data into files containing calibrated spectra with first-order baselines removed. These cubes form the level-1 data products that will be distributed to CO-PIs and released to the public. Level-1 data will be processed further using the aips++ package and its single dish extensions, with IDL routines, IRAF, or with custom software. These programs can be used to extract channel maps, images with a selected velocity integration range, or spatial-velocity image files. These data products will be archived on DVDs and will form the basis of level-2 data products to be released within two years of data acquisition. Graduate students and post-docs will be used and other collaborations will be established during the course of this survey to help with the data reduction and analysis. ARO will develop algorithms that: (i) derive the excitation conditions and column density of the gas along all lines of sight; (ii) extract catalogs of clouds and substructures, bound cloud cores, filaments, shells, partial shells, cometary shapes, and other morphologies; (iii) evaluate the effects of line-of-sight confusion due to unrelated objects; (iv) extract lists of cloud cores and outflows associated with objects selected from other catalogs; (v) evaluate basic structural properties of molecular gas in the Galaxy; and (vi) analyze large scale motions in terms of galactic structure models such as spiral density wave theories, and supershell models. This consortium will seek the help and collaboration of members of the research community to help develop some of these post-processing tools.

III.5.2 Chemical Composition of Circumstellar Disks

Line emission from molecules in the (sub)millimeter wavelength range offers unique possibilities to study the formation of stars and planetary systems. Hogerheijde (Steward Observatory Bok Fellow) makes extensive use of this line emission to investigate how the dense cores of molecular clouds originate and collapse, how this collapse leads to stars and circumstellar disks, and what physical and chemical processes occur in these disks; thus determining the initial conditions for a forming planetary system. The KP12m and SMT telescopes provide essential tools for this endeavor. Observing multiple molecular species and multiple transitions gives information of the chemical make-up of the object and physical conditions such as temperature, density, and gas motions. To access smaller scales of a few arcseconds, Hogerheijde employs millimeter-wave interferometers such as OVRO and BIMA. These interferometers are insensitive to emission on more extended scales, and the KP12m and SMT telescopes play an essential role by making it possible to map these more extended scales. Such maps can be combined with the interferometer data, resulting in full sampling of all spatial scales (down to the resolution of the interferometer data). In particular, Hogerheijde is interested in the structure and chemical composition of circumstellar disks (in collaboration with van Dishoeck and others).

Together with Boogert and Blake (Caltech), Hogerheijde is studying inflow and outflow processes on very small scales as probed with 5 μm absorption spectroscopy using the W. M. Keck telescope. KP12m and SMT observations provide the required complement to come to a full understanding of the system (e.g., Hogerheijde 2001 and Boogert et al. (2002) give an example of how single-dish, interferometric, and near-infrared observations together reveal the inflowing motions in a circumstellar disk in L1489 IRS).

In molecular clouds that are actively forming stars, the associated energetic processes such as jets, outflows, and ultraviolet radiation, affect the cloud structure and chemical composition. During this grant period, Hogerheijde will study these environments with the KP12m and SMT to cover the emission on extended scales, so that a full understanding can be reached of how the star-forming activity impacts the cloud and possibly regulates ongoing or future star formation.

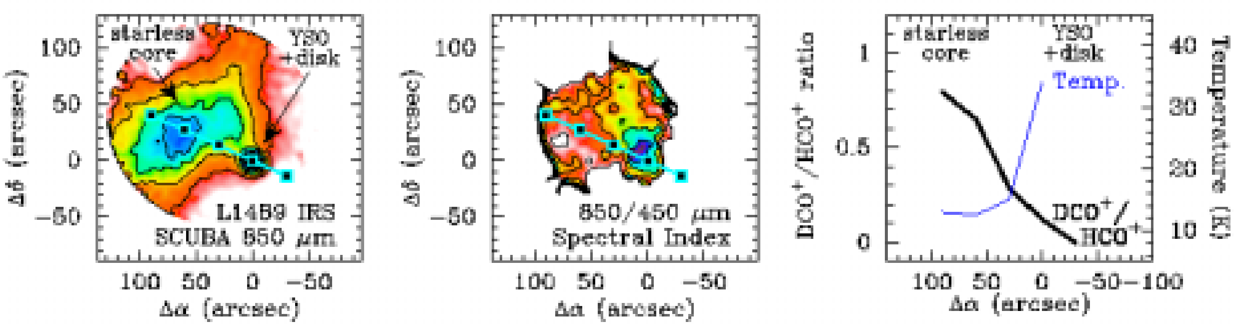


Figure 18. Sensitive chemistry in the YSO L1489 IRS as demonstrated by continuum SCUBA maps (left and middle panel) and SMT 10m spectral line measurements of HCO^+/DCO^+ (right panel). The ratio changes dramatically from the starless core to the YSO.

As an example, Hogerheijde (2002) observed with the SMT a strip across the young stellar object L1489 IRS and the adjacent starless core in HCO^+ and DCO^+ J=3→2 (see Figure 18). Earlier SCUBA data (Hogerheijde and Sandell 2000; left) of the 850-micron continuum emission and the 850/450-micron spectral index (middle) help to constrain the temperature of the material (right). The temperature increases sharply from the cold starless core to the warm disk surrounding the YSO. The D/H ratio as traced by DCO^+/HCO^+ drops dramatically over this distance, illustrating the sensitivity of deuterium chemistry to temperature. SMT data will be used to investigate the gas temperature, ionization, and chemistry in a variety of protostellar environments.

III.5.3 Remnant Disks Surrounding Post T Tauri Stars: A Search for Cold Dust

Circumstellar disks surrounding young stars are thought to be the sites of planet formation. What are the conditions in circumstellar disks and timescales required? This fundamental question can be addressed through evolutionary studies of the dust content in circumstellar disks surrounding young stars. M. Meyer (SO) will continue searches for remnant dust in the outer regions of circumstellar disks surrounding post T Tauri stars. An understanding of the evolution of dust from the accretion disk phase, through planet-building, and finally the debris disk phase, could place important constraints on theories for planet formation.

Near-infrared excess emission from YSOs at wavelengths between 1 and 5 μm (e.g. Lada and Adams 1992) traces dust and gas from the stellar surface out to a distance of ~0.1 AU and can be modeled as a circumstellar disk heated both by the central star and viscous dissipation from active accretion (e.g. Meyer et al. 1998). In a recent study of several clusters, Hillenbrand and Meyer (1999) derived a 1/e timescale of 8 Myr for active accretion disks in a young cluster. In contrast, the evolution of dust disks in the terrestrial planet zone from 0.3-3.0 AU, is poorly known. A mid- and far-infrared photometric survey aimed at deriving the timescale for dissipation of optically thick outer disks around young stars (Meyer et al. 2000), made with ISO at 25 to 60 μm detected 14 stars out of a sample of 97. The results imply that optically thick disks in the terrestrial planet zone surrounding young stars dissipate, or coagulate into larger bodies on timescales comparable to the termination of the disk accretion phase.

Meyer and colleagues propose to obtain sub-millimeter photometry for the "transition objects" detected in these ISO surveys. These stars, aged 5-300 Myr, lack near-infrared signatures of inner accretion disks, but appear to have warm dust in the terrestrial planet zone between 0.1-3.0 AU. ISO was sensitive to the presence of material of mass 0.01-0.1 M_{earth} in the inner regions of these disks. Assuming standard disk density and temperature distributions, ~ 10^{-3}-10^{-4} M_{Sun} in cold gas + dust lies between 10-100 AU. With the 19-channel bolometer array, a mass detection limit of $M_{DUST} < 4 \times 10^{-7}$ M_{Sun} in three hours of on-source integration time at 870 μm should be reached. Even if not detected, meaningful constraints will be placed on the amount and distribution of dust in these remnant disks. This survey complements the SIRTF Legacy Science Program, *The Formation and Evolution of Planetary Systems: Placing Our Solar System in Context* of which Meyer is the principal investigator.

III.5.4 Millimeter Studies of Infrared Dark Clouds (IRDCs)

The ARO is an integral part of a long term study of IRDCs by S. Carey (IPAC), Butner (SO) and others. The IRDCs are large (>0.1 pc), cold (T~7-20 K), dense (N~10^6 cm^{-3}) molecular cores identified by 1-4 mag extinction at 8-21 microns, against the diffuse midIR emission in the Galactic plane. Previous observations of the IRDCs with the KP12m have characterized their gas properties (Egan et al. 1998; Carey et al. 1998) and revealed substantial depletion of molecular species (Carey et al., in preparation). Additional studies with the JCMT and SMT have identified compact sub-mm sources with outflow/infall signatures suggesting class 0 (or earlier) protostars (Carey et al. 2000). The compact sources are massive; it is likely that IRDCs are progenitors of massive star formation. The current projects that will be continued during the grant period are (i) CS (3→2) observations in support of a catalog of IRDCs and (ii) a study of deuterium fractionation.

A catalog of IRDCs identified in the MSX Galactic Plane Survey is currently in preparation. Approximately 4000 candidate objects have recently been observed at 8 microns. Initial observations of 900 of the 1800 northern IRDCs were conducted in May 2002. CS (3→2 at ~147 GHz) is a good and efficient tracer of dense gas (the KP12m and the SMT are the only US single dish mm telescopes that can observe this tracer). Based on a cursory analysis of the data, 40% of the candidates contain significant molecular gas. Further investigation of the remaining cores is needed to determine if the gas is depleted and/or the mid-infrared extinction is anomalous.

IRDCs are ideal to study deuterium fractionation chemistry as they contain large columns of cold, dense gas, with temperatures of order 10 K at which deuterated species are expected to be abundant. A smaller fraction of the cores are internally heated by embedded protostars to T ~20-40 K. Butner and Carey have begun a program to examine 80 IRDC cores previously detected at 850 μm using the J=1→0 lines of DCO^+ (72 GHz) and $H^{13}CO^+$ (86 GHz). Over 50% of the cores observed thus far contain significant DCO^+ emission. The brighter sub-mm cores contain dense gas but no DCO^+ emission. A small fraction of the IRDC cores contain neither molecule. It is likely that the gas is severely depleted in these objects. Completion of the survey and its analysis will be carried out.

III.5.5 Probing Protoplanetary Disks with Vibrationally Excited Emission Lines

Sub-mm molecular lines are associated with rotational excitation of the lowest vibrational state. However, several vibrationally excited molecules, such as CS, H_2, CH_3CN, and HCN have been detected in the ISM. Since these vibrational bands lie typically >1000 K above the ground state, their excitation requires either hot, dense gas (perhaps shocked) or radiative pumping. Since these excitation requirements are only expected to be fulfilled in a compact region close to an embedded source, vibrationally excited molecules with sub-mm rotational transitions are excellent probes of the physical conditions in these objects. Walker and students have observed a sample of young stellar objects, searching for the (0,1,0) and (0,2,0) vibrational transitions of HCN($J=4\rightarrow3$) with the SMT.

Thirteen objects were detected in the HCN ($J=4\rightarrow3$) $v=(0,1^{1c},0)$, but none from the $(0,2^{c},0)$. Collisional excitation requires extremely high densities $N > 10^{11}$ cm^{-3} and high temperatures. If it is possible to determine that the excitation mechanism is collisional in nature, then it can be shown that regions of extremely high density and temperature exist in protostellar sources. Smooth accretion disk models cannot account for densities and temperatures this high. Shock heating and compression are implied. These physical processes may indicate structure formation in the disk, like clumps, gaps and spiral density waves.

The v=2 lines can establish the excitation mechanism. Two of the transitions are not permitted for radiative processes. In addition, radiative pumping tends to populate the lower energy levels fairly uniformly. In this case, one v=2 line should be observed with similar brightness to the v=1 lines. In the case of collisional excitation, all three v=2 lines should be seen, but at much reduced intensity compared to the v=1 transitions. A follow-up program at the SMT is ongoing to observe the v=2 lines, along with the $v=(0,1^{d},0)$ line. Walker plans to continue to study vibrationally excited emission toward protostellar systems, beginning with known binaries with massive disks, working down to single, low-mass objects. These observations will better constrain disk models and guide future higher angular resolution observations with the SMA and ALMA.

III.6 Comets and Solar System Origins

Millimeter observations of comets offer a unique method by which to examine the chemical composition of the early solar system. The host of molecules that sublimate from the comet's surface as it passes by the sun are thought to be representative of the dense protostellar disk. Bright comets typically come into the inner solar system at a rate of about two per year, and require "target of opportunity" scheduling at telescopes. ARO offers such scheduling, made practical by remote observing, and the added attraction of simultaneous, multi-wavelength measurements at two facilities. During the past two years, a significant amount of time was devoted to cometary observations.

H. Butner and S. Charnley have used the SMT and KP12m for simultaneous observations of two recent comets (C2000/WM1 and C2002/C1). With the telescopes located so close together, it is possible to measure multiple lines at the same time. This means that while the SMT is measuring a high transition line (like HCN $4\rightarrow3$), the KP12m can be observing the lower transition line (HCN $3\rightarrow2$ or HCN $1\rightarrow0$). In the case of C2002/C1, the HCN $3\rightarrow2$ and HCN $4\rightarrow3$ lines were observed a number of times with the KP12m/SMT pair. These observations found that the HCN line peaked off the nucleus (Charnley et al. 2002, Butner et al. 2002). In addition, Butner et al. (2002) found that the HNC/HCN ratio was the highest ever seen for a comet during one part of the orbit - but that the comet's HNC/HCN ratio varied significantly as a function of the comet's heliocentric distance. Such observations are extremely useful to indicate where the various observed molecules can originate and what are likely parent species. Other observations of CS $5\rightarrow4$ and CH_3OH at both SMT and KP12m are currently being reduced. In the case of the CS $5\rightarrow4$ emission, it seems to be extended as well. These observations will test how well various chemical models predict the relative abundance and distribution of the observed species.

The SMT can also observe the dust continuum of comets. Mapping of the dust emission at 870 microns can allow one to look for correlations or anti-correlations in various molecules and the dust. Because the SMT can easily switch between the thermal and molecular line observations, this promises to be a fruitful area. Comet C2002/C1 was not particularly bright at 870 microns, but was detected by Butner and collaborators. These data are currently being reduced for comparison with HCN and CS maps of the comet.

Hogerheijde is closely involved with millimeter-interferometric studies of molecular-line emission from comets as well. These observations, carried out with the OVRO and BIMA arrays, probe the small (<5") scales of the emission and reveal details of the chemistry and the evaporation process such as jets (e.g., Blake et al. 1999; de Pater et al. 2000). Single-dish observations with the KP12m and the SMT fill three essential roles connected with the interferometry: (i) they monitor the cometary activity over a long time baseline, allowing scheduling of interferometric observations; (ii) they measure the large-scale emission to which interferometers are insensitive; and (iii) they can be part of a campaign where a comet is observed simultaneously in the same (or complementary) tracers and/or transitions. The last offers the unique capability of obtaining an instantaneous snapshot of the cometary coma on many scales and through many tracers. Joint, simultaneous observations with BIMA and OVRO have already been carried out successfully by Hogerheijde et al. These have the potential of merging different `array configurations' and in that way tracing a wide range of spatial scales.

For the next few years, comet observations will remain a high priority as they appear in the solar system. Studies of the HCN/HNC ratio, searches for HCO^+ to investigate ion molecule chemistry in the comet coma, and observations of organic species related to astrobiology are key targets for the next comet visits. These investigations will be carried out under the leadership of Dr. H. Butner (SO), Dr. M. Hogerheijde (SO) and Professor Susan Wyckoff at Arizona State University, who will be on sabbatical at the Lunar and Planetary Lab at the UA during 2003.

III.7 Participation of the Outside Astronomical Community

At least 50% of the ARO time supported by NSF through this proposal will be made available to support projects proposed by the astronomical community and will be selected on a merit basis by the Time Allocation Committee (TAC). Given that there were over ninety external users of both telescopes this past season, including ten graduate students, a large participation from the outside community is expected. A few of the many ongoing external programs are briefly presented.

Planetary Atmospheres. Millimeter spectral line observations of planetary atmospheres with the KP12m have provided invaluable long-term (>10yrs) measurements regarding unexplored aspects of planetary atmospheres. The temporal coverage and sensitivity of these observations are required for effective studies of climate, photochemistry, and transport within the atmospheres of Mars (Clancy et al. 2000), the Earth (Clancy et al. 1999), and Venus (Clancy et al. 1999). The unmatched combination of excellent receiver/spectrometer performance, and flexibility of operations at the KP12m supports unique explorations of molecular physics, photochemistry, and transport within the Earth's middle atmosphere. It is crucial that these synoptic observations be continued.

KP12m Observations Complementary to BIMA Programs. Single dish observations complement interferometric studies in two important ways: i) by probing extended, diffuse molecular emission, to which the array is insensitive and ii) by providing independent flux measurements, allowing mass determinations and comparisons with other observations. During the past observing semester (February–June 2002), the KP12m was employed for five BIMA related programs that include the thesis work of Adam Leroy, Joshua Simon, Jonathan Swift, Eric Rosolowski, and Nate McCrady (see Figure 19 for an example).

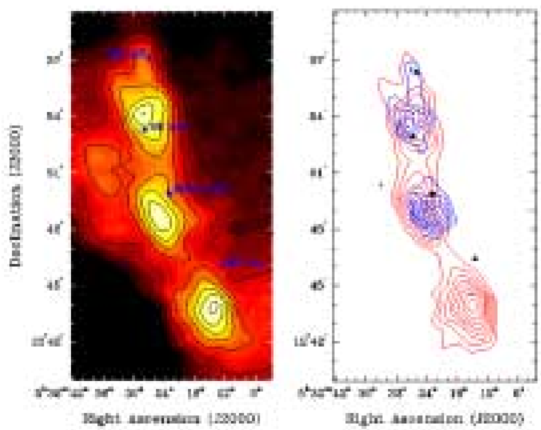


Figure 19. A KP12m OTF map of CO emission of RNO43 (10′ × 20′ region). The red and blue shifted line wings (right) are coincident with the known HH objects (▲). (Courtesy of J.Swift and W. Welch of U.C. Berkeley).

IV. Proposed Technical Developments

The science proposed in the previous section presents a number of technological challenges that must be addressed before it can be accomplished satisfactorily. In this section, new developments, many of which are already in advanced stages, are discussed which will allow ARO and its associates to achieve their scientific goals. A joint effort of ARO's receiver laboratory, Steward Observatory Radio Astronomy Laboratory (SORAL), and Haystack Observatory (for mmVLBI) make-up the critical components for this endeavor. The ARO is responsible for technical support of both the SMT and the KP12m; SORAL is chiefly involved in new, innovative engineering projects, especially array receivers like the 7-channel, 345 GHz DesertSTAR; and Haystack Observatory is working on advances necessary to extend VLBI into the 1 mm region (section III.3). Graduate student participation is a key component in much of this work, where C. Groppi is working on the DesertSTAR receiver for his Ph.D. thesis, while other graduate students (D. de Lill and C. Savage) have assisted H. Fagg with SMT receiver development.

The major thrust of new technical developments is to (i) cover the entire frequency range 130-1000 GHz at the SMT, (ii) construct a versatile 2 GHz bandwidth filterbank for the SMT, (iii) replace the control system of the SMT with an upgraded version of that used at the KP12m, including a 10-fold increase in data acquisition and the option for remote observing, (iv) upgrade the 3 mm receivers for the KP12m to high electron mobility transistor (HEMT) amplifiers and (v) build and develop SIS array receivers for the SMT, including DesertSTAR. Most of the technical developments focus on the SMT because the KP12m already has continuous frequency coverage from 65-300 GHz in dual channel, single sideband SIS mixers, and a suite of backends that include 30 kHz through 2 MHz filterbanks and the Millimeter-wave Autocorrelator (MAC). At the SMT, dual channel, single sideband SIS mixers will be used to cover the window of 130-660 GHz, and a single channel Hot Electron Bolometer (HEB) will cover the window of 660-1000 GHz. A summary of new and current receivers at the SMT is given in Table 4. The 2 GHz filterbank will be designed to operate as a single 2048 MHz unit, 2 × 1024, 4 × 512, or 8 × 256 channel backend. Hence, it can accommodate the 7-channel array, or be used with the HEB for extragalactic studies, where its stability and wide-band properties will be critical. This backend will be a tremendous improvement in bandwidth, stability and flexibility over the some of the existing spectrometers: filterbanks (from MWO) and the 1 MHz AOS.

Table 4. Current and Future SMT Heterodyne Receivers

	Existing			Planned		
Wavelength (mm)	Frequency (GHz)	T_{Rx}(DSB) (K)	Channels	Frequency (GHz)	T_{Rx}(DSB) (K)	Channels
2	---	---	---	130-170	20	2
1.3	210-275	100	1	200-300	40	2
0.8	320-375	125	2	300-400	50	2
0.6	430-490	150	1	400-500	80	2
0.45	*	---	---	550-660	200	2
0.37	*	---	---	690-1000	450	1

* This region currently covered by HEB on loan from the CfA.

The overall ARO plan is to employ the SMT for observations above 1.3 mm, using the new receiver systems. Of particular importance is the 0.8 mm band, where galactic and extragalactic CO (J=3→2) and CS (J=7→6) measurements can be routinely carried out. Equally important is the 0.6 mm region, which contains the CI fine structure and CO (J=4→3) transitions. Astrochemistry projects will benefit from the frequency agility of the receivers, the high sensitivity of the dual channel mixers and most importantly from image sideband rejection. The KP12m will be used at frequencies below 1.3 mm. Some frequency overlap, however, is essential for mm-VLBI, hence the continued construction of the 2 mm receiver for the SMT. This system will also be used for spectral line studies at the upper end of the 2 mm band (HCN: J=2→1; HCO^+: J=2→1), where the atmosphere becomes quite opaque.

IV.1 SMT Receivers and Backends

IV.1.1 A New Dual Channel, Single Sideband Receiver System for 130-660 GHz

The 130-660 GHz receiver system at the SMT will be placed in two separate dewars (130-300 GHz and 300-660 GHz). The lower frequency system is near completion (see Figure 20). This receiver was tested on the SMT early in 2002 in the 2 mm band and was subsequently used for the recent sucessful VLBI session. It will be installed on the SMT in its full capacity in Fall 2002.

ARO intends to implement a second (high band) receiver system to cover the remainder of the frequency range (300-660 GHz); it is based on the same mechanical layout as the first. As such, the design is already well advanced. It is to follow the general formula of room temperature optics, Gunn local oscillators with diode multipliers, cooled SIS mixers and IF amplifiers, and a room temperature IF processor. Bias circuits, control circuits, and monitoring circuits are also of similar design to those being incorporated in the first receiver. One of the main features of this receiver is the termination of the unwanted sideband. The actual sideband separation occurs in the room temperature quasi-optic assembly mounted to the top plate of the dewar. The two sidebands will be separated by 10 GHz, thus they are readily separated spatially and sent down different paths by a Martin Pupplet Interferometer. The unwanted sideband is terminated on a 4 K load through a vacuum window in the dewar lid while the desired sideband is directed into the receiver through a different window, as shown in Figure 21. The Martin Pupplet tuning will be automated through the receiver control system.

Figure 20. The 130-300 GHz receiver prior to testing at the SMT showing the 2mm inserts used for VLBI.

Owing to the broadband nature of the high band receiver, the local oscillator will be split into three bands, 300-400, 400-500 and 550-660 GHz. With the recent increase in the availability of tunerless diode multipliers, the local oscillator system design has been greatly simplified. The fundamental oscillator in each band will be a phase locked Gunn. Automated band selection, frequency adjustment, and power leveling will be provided by the receiver control system.

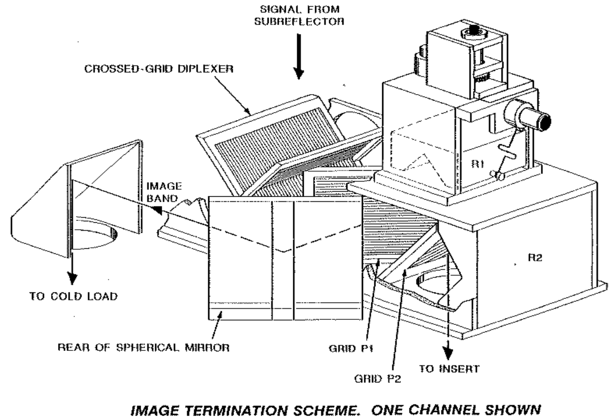


Figure 21. A conceptual drawing of a single channel Martin Pupplet Interferometer.

The cooled electronics will be housed in a dewar equipped with a three stage cryogenic system. A Gifford McMahon cycle cooler will be used for the first two stages. Cooling from the first stage is predominately for the infrared shielding. The second stage will provide helium gas pre-cool prior to liquefaction in the third stage. A Joule Thompson expansion cooler based on the very temperature stable NRAO design will be the third stage. This system has already been tested in the SMT lab and achieved greater than 1.5 watts of cooling capacity at 4.2 K

Like the LO systems, the frequency range of this receiver is too large for a single pair of tunerless SIS mixers, therefore the band has been divided into three and consequently six mixers will be required to cover all bands and polarizations. The chosen frequency divide is to mesh with the local oscillator bands. The IF output of the mixers will give a 2 GHz instantaneous bandwidth centered around 5 GHz. The IF signal will be amplified by cooled HEMT amplifiers.

Room temperature 4 GHz to 6 GHz IF processor electronics will be provided to achieve the desired receiver output level and band shape. There are several backends available and appropriate signal conditioning and distribution electronics will be provided. Enough flexibility is to be built in to accommodate planned future spectrometers.

The receiver and its subsystems will be mounted on a moveable cart. This will provide the means to cool the receiver prior to installation and then move it into position, as well as allow this and other receiver systems to be interchanged in a short period of time. A large flange adapter plate will provide accurate location of the receiver with regard to the telescope Nasmyth focal point.

In the first year of this proposal, ARO plans to complete the mixer pair centered at 345 GHz. This is the largest part of the project involving the majority of the infrastructure items. This first pair will soon be operational on the telescope and the remaining items will be completed in the lab and installed at the telescope as they become available. The second year of the project will see the completion of the infrastructure items and have the system working on the telescope to beyond 500 GHz. During the final year, the high frequency pair will be installed and the receiver will then have frequency coverage to around 660 GHz. This is a mature program designed to make a giant step forward in the observing capabilities of the SMT and is essential to carry out the proposed scientific programs.

IV.1.2 2 GHz Bandwidth Filter Bank

Much of the proposed science program requires a very stable, broadband backend to complement the new suite of receivers being built for the SMT. The science programs that will clearly benefit from this backend include extragalactic spectral line work, searches for new interstellar molecules and those programs that involve measurement of low intensity features. For this purpose, a 2048 × 1 MHz filter bank is under construction that is based on a modified design from Jodrell Bank. This spectrometer will be a flexible system that is fully compatible with the dual polarization front ends as well the multi-beam receivers. Furthermore, it can be built and maintained by the current ARO staff without the need for outside expertise.

The filterbank is divided into three systems. The IF processor will divide the incoming signal from the receiver into eight 256 MHz wide sub-bands. These sub-bands can be steered by the control system to accommodate the receiver requirements. The eight bands can be used in parallel to accommodate up to an eight-beam receiver, or they can all be used in series to produce a single band 2 GHz wide. It is expected that the usual operating mode would be to use the filters in two banks of 1024 channels. This mode provides a broadband, stable spectrometer for use with the dual polarization receivers coming online at the SMT over the next few years. The filter cards will all be identical, with each of the 64 cards having 32 × 1 MHz channels plus necessary control and monitoring circuitry.

The cards are to be in logical groupings of eight with each grouping fed by an output from the IF system. Outputs from the filter cards are passed to the digitizer section. The digitizer section is currently being designed, but in general terms it will be a 14-bit digitizer/multiplexer occupying 32 cards in four bins. The design of the digitizer/multiplexer will, where possible, follow the same hardware approach as the AOS interface for the new control system (see section V.5). This control system is currently nearing completion and will be installed at the telescope later this year. The use of common hardware reduces the design time and allows for a smaller spares inventory.

Work on the filter bank system has already begun. Steward Observatory has supplied funding for the first two 256 channel blocks of the filter bank, necessary IF processor hardware, digitizer hardware and many of the common hardware items. In the first year of the project ARO will complete the IF processor and the next two 256 channel blocks of the filter bank. The second year will see the remaining four 256 channel blocks of the filter bank completed.

IV.2 Kitt Peak 12 Meter Development

IV.2.1 3 mm Receiver HEMT Upgrade

The existing 3 mm receiver uses four SIS mixers to cover the frequency range 68 GHz to 115 GHz. This receiver has been in use at the KP12m telescope for many years and shares a dewar and some optics with the 2 mm receiver system. However, better technology now exists for receivers in the 3 mm bands, namely that of HEMT amplifiers which have greater stability, larger bandwidth and are inherently more reliable without sacrificing sensitivity. Because observations of such transitions as CO $J=1\rightarrow0$ (115 GHz) and DCO^+ (72 GHz), play a critical role in the science proposed here, it is essential for ARO to maintain a dependable state-of-the-art 3 mm system at the KP12m. It is for this reason, a replacement for the old 3 mm receiver is proposed. This new receiver will utilize cooled HEMT amplifiers and Schottky mixers in a single dewar. By use of two orthomode transducers in the new system, the room temperature optics will be much simpler than what is currently employed. Single sideband operation will be an integral part of the system, but will be achieved by mixing rather than tuning. It is planned that the entire 3 mm receiver system be installed in a separate dewar cooled to 20 K using commercially available refrigerators. This would further enhance telescope reliability by reducing the maintenance currently required on the on the older, more complicated 4 K systems.

A down-converter and IF processor must be built to handle the large instantaneous bandwidth available from the receiver described above and to maintain compatibility with the existing spectrometer input requirements. As no spectrometer or other receiver replacements are planned for the KP12m at this time, this is the most cost effective approach.

No hardware expenditure costs are planned for the first year of this proposal although detailed designs will be drawn-up during this period. It is expected that during the second year, the detailed design work will be completed and long lead-time hardware purchased. Construction will also begin during the second year. The third year of the project will see the completion of the receiver. This will be made possible when work on other projects ramps down at the end of the second year of this project.

This upgrade will greatly improve observing efficiency at the KP12m by reducing the complexity of the system both mechanically and electrically (see Figure 22), which in turn will result in higher system reliability. As an added bonus, tuning times will be significantly reduced and can be fully automated.

Figure 22: The complexity of the existing 3mm (shown above) will be greatly simplified both electrically and mechanically with the HEMT upgrade.

IV.2.2 Local Oscillator Reference Upgrade

The ARO intends to upgrade the current local oscillator system at the KP12m to enhance future 2 mm VLBI results and make possible the proposed 1.3 mm and above VLBI observations. There are two main reasons for performing this upgrade: (i) to improve the stability of the phase lock and (ii) to improve the phase noise performance to a level adequate for very high frequency VLBI measurements. The phase lock loop circuitry used for the Gunn oscillator control uses a 2 GHz reference frequency from a rather ancient Fluke synthesizer. This frequency is multiplied by some integer (up to 58) and is compared with the Gunn frequency. This upgrade proposes utilizing an 8 GHz reference frequency, which reduces the multiplier number by a factor of four, which results in a large improvement in signal to noise ratio in the Gunn phase lock system. By doing so, it will also lead to improved phase noise performance from the LO systems on all of the receivers. This results from the lower multiplication factor and the use of low phase noise sources. Modifications to the local oscillator lock box (of NRAO design) to incorporate the change to a higher Gunn reference frequency will be required and have been planned as part of the upgrade.

IV.3 DesertSTAR: A 7 Beam 345 GHz Heterodyne Array Receiver

Due to the prevailing physical conditions in the interstellar medium, the 870 μm atmospheric window is one of the richest in the submillimeter portion of the spectrum. An array designed for this wavelength range will make excellent use of available telescope time and provide a new perspective on stellar, chemical, and galaxy evolution in the present, as well as past epochs. For these reasons, SORAL is building a hexagonally packed, 7-channel 870 μm array receiver, DesertSTAR, for the SMT. Each array pixel produces a diffraction limited 22″ beam. The separation between adjacent beams on the sky is 2fλ. A footprint of the array on the star-forming region M16 is shown in Figure 23.

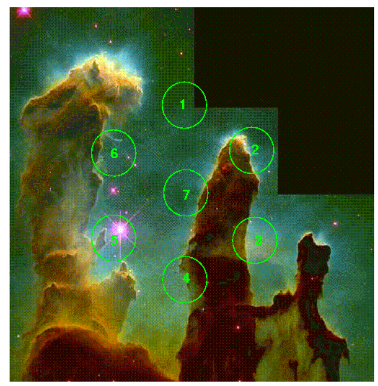


Figure 23. The array footprint of DesertSTAR overlaid on a HST image of M16. Each circle represents the FWHM of the diffraction limited 22” beam.

The array utilizes fixed-tuned, SIS waveguide mixers with diagonal feedhorns. Each feedhorn has a phase correcting, dielectric lens mounted in the telescope's focal plane. The mixers (designed by G. Narayanan, FCRAO) have an IF output of 4-6 GHz. A LINUX based PC is used to monitor the instrument's performance and control the bias voltages (SIS, IF amp, magnet) of each receiver channel. The mixers, low-noise IF amplifiers (manufactured by Miteq Inc.), and optics are cooled to 4 K by a closed-cycle, JT refrigerator built in collaboration with NRAO Tucson. Initially, the array will operate in double sideband (DSB) mode and use a Mylar beamsplitter for local oscillator (LO) injection. The University of Cologne has fabricated a phase grating that will split the output of the LO into 7 equal intensity beams that match the mixer lay-out. Calculations indicate that, with the phase grating, LO injection via a beamsplitter will provide ample power to drive the 7-element array. The solid-state LO chain for the array is being provided by N. Erickson (FCRAO) as part of the UMass contribution. Ultimately, SORAL plans to upgrade the array to dual polarization by using orthomode transducers (OMTs) on the output of each horn. The OMTs split the light collected by a feedhorn into two physically separate horizontal and vertical components. Each component goes to its own mixer. The beauty of this approach is that the same feedhorn is used for both polarizations, eliminating alignment problems. The array cryostat will be mounted in a rigid, adjustable framework that will be bolted to the right elevation flange of the SMT.

The first engineering run with the array is planned for October 2002. Regular observing with the array on the SMT will begin in January 2003. Initially, the existing spectrometers at the SMT (3-AOS, 3-filterbanks) will be used for the array backend. They will be supplanted by the 2 GHz Filterbank system described previously. Walker and colleagues plan to propose to the NSF ATI program for funds to build/purchase a wider bandwidth spectrometer capable of processing the full 2×7 GHz of IF provided by the array. Until then the array will be used for a wide variety of galactic astronomy projects; everything from probing conditions in circumstellar disks to mapping giant molecular clouds. It will also be used in the galaxy mapping key project. DesertSTAR will utilize the 2 GHz filterbank as a backend, as well as a correlator on loan from UMass as a backup. Funds are requested in year one to build the IF processor for the correlator.

IV.4 Astrochemistry Spectroscopy Laboratory

In addition to the receiver laboratories, Ziurys has a mm/sub-mm spectroscopy lab with three fully-functioning spectrometers, currently operating in the range of 65-810 GHz. Although this facility is funded by other sources, it nonetheless is available for laboratory measurements for observatory projects as needed. This facility is unique to university radio observatories.

IV.5 A New SMT Control System

The current antenna control system is based on a single VAX computer interfaced to the antenna control hardware and spectral line backends mainly through CAMAC electronics packages. The CAMAC electronics are obsolete, difficult to maintain, unreliable, and no longer supported. Moreover, when the control system was first written, the computing power in microprocessors was very limited. Only the antenna servo loop was handled in the microprocessor, other time critical calculations were carried out in programs running on the VAX, which in the current design, must monitor and update the microprocessor commands four times a second.

A primary goal of the ARO is to completely replace the current control system with modern hardware and utilize state-of-the-art operating system technology. ARO is modeling the new control system after that of the NRAO 12-meter. The most critical tasks will use Linux base x86 hardware. It will be one of the most modern of its kind, using a highly distributed network based control system, consisting of multiple processors running a variety of operating systems from Solaris to Linux. It will thus represent the state-of-the-art in heterogeneous design. All functions of the system, including remote observing, are presented to the observer through interactive, intuitive graphical user interfaces. Some of the new control system features are listed below.

Remote Observing: Remote observing will be built in from the start at the SMT. An astronomer will be able to logon to the telescope from virtually anywhere in the world and set up a software package in a matter of seconds that entirely mimics the system at the site. This capability is augmented by highly skilled telescope technicians on the site who perform all necessary local functions for the observer, such as tuning the receiver to a new frequency. The observer interacts with the site technician via a "chat window". Even a laptop computer can be used for remote observing. A unique software/hardware package has been developed over the years for this purpose, and has been thoroughly tested by observers from all over the world who use the remote capabilities. Moreover, it allows for extreme flexibility in telescope schedule, and is perfect for long-term monitoring program and/or sudden developments, such as the appearance of a new comet.

Parallel Processing: Because the new control system is of a distributed design, the processing power is magnified many times over. This also lends itself to parallel processing. Many different tasks are carried out simultaneously. This design allows the backend computers to concentrate strictly on the process of data taking. Tasks such as graphical displays, file servers and on-line analysis are handled by separate processes in other computers. So for instance, all the while the file server is writing the just completed scan disk, the on-line analysis is reducing it and the graphics engine is displaying the results, the backend is already taking the next scan. In fact, while observing, the backend never stops.

Efficiency and Data Rates: At present there are many inefficiencies in the current SMT system. Spectral line beam switching has an inherent inefficiency that ranges from 25 to 50%. This is primarily due to the non-synchronous nature of the hardware. Also large periods of dead time exist at the beginning of and in between scans. Both these and other minor inefficiencies will be addressed during this upgrade. ARO expects at least a factor of two improvement. Furthermore, the new control system will dump data at the rate of 10 times/second. This will allow for OTF maps of the same rms value to be taken at 1/20 the current time.

Current State: During the fall and spring observing season, ARO has had several successful tests on the telescope using the new drive system. Other sub-systems have been tested as well. During the summer shutdown of 2002, the new control system will be installed at the SMT. Full implementation of all aspects of the new control system are on track for a mid September 2002 installation.

IV.6 Long Term Strategy

A strong technical program in radio astronomy linked with the education needs of the university is emerging at the UA. The ARO has recently made a strong commitment to the future by assembling a core technical staff consisting of several highly experienced receiver RF engineers (H. Fagg, and G. Grahame, formerly of Parkes Observatory and J. Cochran formerly of NRAO), programmers (T. Folkers formerly of NRAO and T. Sargent formerly of Synergy Inc.) and a digital engineer (D. Forbes formerly of Synergy Inc.). Therefore the expertise is available to bring these proposed technical projects to fruition. The success of the recent VLBI run is indicative of a coherently functioning technical group. The UA machine shop is aiding in this endeavor as well by developing competent and high quality machining. Integration of graduate students from SORAL (C. Groppi, A. Hedden, C. and C. D'Aubigny) and other groups (D. de Lill and C. Savage) with the technical staff is already routine.

The long term goals of ARO are two fold: (i) to build and maintain state-of-the-art receiver systems to attract graduate students, post-docs and young faculty to the UA in the field of Radio Astronomy and (ii) to guide and foster new technical developments in Radio Astronomy though student, faculty, and staff participation. In this sense, the currently proposed technical programs lay the foundation for future growth at the ARO and the UA.

V. Management Plan

The UA proposes to integrate the management of the SMT and the KP12m to achieve a more cost-effective organization. The change takes advantage of a change in the SMT organization following the decision of the Max-Planck-Institut für Radioastronomie to reduce its share of the SMT to 25% beginning in July 2002. Dr. T. Wilson, the current SMT Director, is returning to Bonn at that time. The UA, through Steward Observatory, accordingly becomes the lead partner.

The KP12m has been operated by the UA through Steward Observatory since August 1, 2000 following NRAO's decision to cease operating the KP12m as a national facility. The telescope has been on loan from NRAO since that time and the transfer of ownership is being formalized with the NSF. Dr. L. Ziurys has been Acting Director of the KP12m since August 2002. Support for the operation has been provided by the Research Corporation, the UA and through a bridge-funding grant ($400K) from the NSF.

V.1 Proposed Management Structure

Assuming this proposal is supported by the NSF, the proposed ARO will consist of the SMT and the KP12m facilities. In addition to the faculty at the UA, it will also involve active participation of scientists from Arizona State University, the University of Colorado and M.I.T. The scientific and technical work of the Observatory will be coordinated by a Director and Scientific Council; they will report to the UA Vice President for Research (R. Powell) through the Director of Steward Observatory (P. Strittmatter). The Director of ARO will be L. Ziurys, effective May 26, 2002, who will also chair the Council. Initial Scientific Council members would be: A. J. Apponi, J. Bally, J. Bieging, S. Doeleman, P. Strittmatter, R. Wielebinski, L. Ziurys.

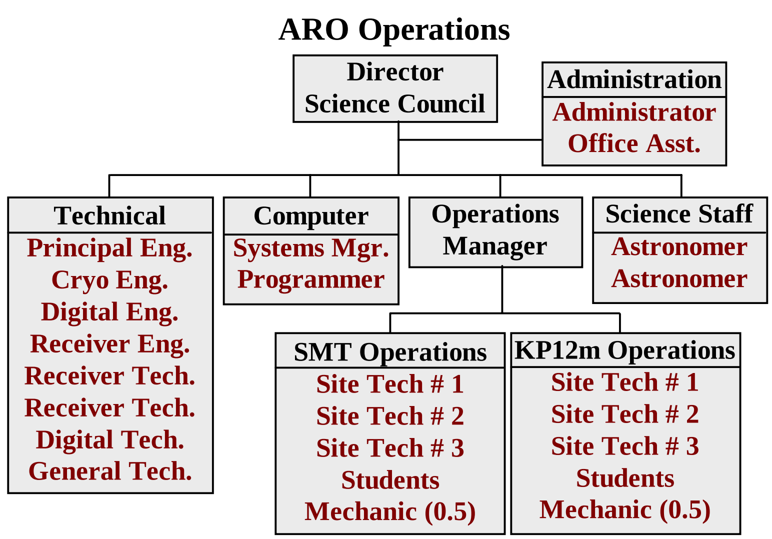


Figure 24 Management plan for the ARO.

The ARO support staff will be structured as shown in Figure 24. H. Fagg will serve as Chief Engineer, T. Folkers will be responsible for Telescope Operations, including the telescope control systems and remote observing activities and W. Peters will serve as chief software engineer. They report to the ARO Director as do the staff astronomers. Logistical support on Mt. Graham is provided to ARO through the Safford-based Mt. Graham International Observatory group headed by J. Ratje.

Several postdoctoral fellows (two requested in this proposal) and graduate students (four requested here) will participate in all aspects of the program ranging from key projects to operations to public outreach. ARO also plans to involve undergraduates in appropriate parts of the program (see section VI).

V.2 Science Program Management

Responsibility for the key science programs has been agreed as follows:

External Galaxies	B. Vila Vilaro, A. Zabludoff
Astrochemistry	L. Ziurys, A. Apponi
Mm-VLBI	S. Doeleman, J. Bieging
ISM/Circumstellar Matter	J. Bieging, M. Meyer
Galaxy CO Survey	J. Bally, C. Walker

One NSF-funded postdoc will be committed to the Galaxy CO survey project. The second will work either on instrumentation development or the external galaxy survey depending on the applicant list.

V.3 Telescope Time Allocation and Priority Observing

Telescope time on the ARO facilities will generally be assigned on a merit basis through a TAC consisting of the Director, three other Scientific Council members and one outside member, initially Simon Radford (NRAO/ALMA).

For regular observing ARO will continue with the enormously successful priority observing system introduced at SMT by T. Wilson. Under this system, high frequency ($\upsilon > 400$ GHz) observation, or others requiring the very best atmospheric conditions, will be made by whoever is observing when such conditions occur. Priority observing programs take over when the zenith opacity, τ_{225}, as measured by a 225 GHz tipper radiometer ('taumeter'), falls below 0.06. Priority observing ceases when τ_{225} rises above 0.075. Taumeter statistics for the SMT, which are essentially complete for the past 5 seasons (October 1997 to present) show that on average 576 hours (24 full 24-hr days) per year have $\tau_{225} < 0.06$ and 960 hours (40 full days) have $\tau_{225} < 0.075$. We therefore can reasonably expect between 24 and 40 full days for priority observing per year under average weather conditions on Mt. Graham. The same data show that from 1 October through 31 May, on average 50.3% of the time, or 122 full days, have $\tau_{225} < 0.15$, and are well-suited to observations at 345 GHz (i.e., the CO J=3$\rightarrow$2 line). [See the website http://maisel.as.arizona.edu:8080/weather_stats.html.]

If this proposal is funded, some of the ARO observing time will be committed to key projects until they are completed. These commitments are estimated to be as follows:

1) External Galaxies	KP12m	0.75 month
	SMT	0.75 month
2) Astrochemistry	KP12m	0.75 month
	SMT	0.5 month
3) Mm-VLBI	KP12m	1 month (0.5 spring/0.5 fall)
	SMT	1 month (0.5 spring/0.5 fall)
4) ISM/Circumstellar Matter	KP12m	0.5 month
	SMT	0.5 month
5) Galaxy CO Survey	KP12m time	0.75 month
	SMT time when $\tau_{225} > 0.15$ for 230 GHz (~ 0.75 month)	

The amount of time made available to the general astronomical community will be a minimum of 50% of the fraction of ARO support provided by NSF under this proposal. Additional community access will be provided through the Research Corporation contribution.

V.4 VLBI Operations

Science Timeline: The main VLBI scientific thrusts will concentrate on mapping SiO masers in the 1-2 mm bands, observing and potentially mapping other maser species for the first time, and pursuing high resolution detections of the Galactic Center. A projected timeline for VLBI goals can be summarized as follows:

- 129 GHz maser observations using finalized 2 mm receiver system at SMT (Years 1-3).
- Observations of HCN, methanol, water, radio recombination line masers (Year 1).
- Wideband observations on SMT-KP12m-BIMA array (Year 2).
- Long baseline observations on SgrA* (Year 2-3).

VLBI observations will be carried out for a total of 1 month per year split into two week sessions to allow correlation of data during the observations for diagnostic purposes. Longer sessions also limit vulnerability to poor weather.

Tasks: To accomplish these goals, a number of specific tasks will be carried out including:

- Complete 1 mm and 2 mm receiver system at SMT.
- Enhance LO at KP12m and SMT for 230 GHz VLBI.
- Upgrade nine BBCs for wideband VLBI recording.
- Integrate and test Mark5 recorders at SMT and KP12m.
- Assist and advise other sites such as SEST, JCMT and IRAM with Mark5 systems.
- Schedule observations, ship equipment, and support observations at sites.
- Process and analyze VLBI data using the MK4 wideband correlator at Haystack.

Responsibilities: Improvements in the continuum capability and the move to 230 GHz will be implemented in a phased approach over the first year. Drs. Corey and Doeleman will bear primary responsibility for implementing the VLBI specific phase noise improvements at the SMT and KP12m in cooperation with Steward Observatory personnel and in consultation with Dr. Rogers. They will also take delivery of the MK5 recorders and new field system computers and integrate them with the VLBI systems. Drs. Doeleman, Phillips and Corey will travel to SMT, KP12m, and other participating sites to assist with setup and observations. Some elements of the VLBI systems will continue to be loaned from Haystack and these will be shipped to Steward Observatory and back for each VLBI observing session. Titus will be in charge of correlating VLBI data on the MK4 wideband correlator at Haystack for both yearly observing sessions. The MK4 system will be required to correlate the high data rates proposed. Base Band Converter modification will be done by Buretta. Attridge will assist with scheduling observations and with software issues related to export of VLBI data into post production imaging packages.

Both the MPIfR and IRAM will remain close collaborators in these efforts and assist with logistical support of the IRAM 30m and SEST. They will also take responsibility for integrating VLBI systems with the telescope control software at both SMT and KP12m—a critical task led by these institutes for the 2 mm VLBI in April 2002. Contact with the SMA, ALMA, CARMA and LMT groups will continue throughout the grant period to lay the groundwork for their eventual participation in mmVLBI. The technical aspects needed for VLBI at these sites will be explored.

V.5 Overall Funding Requirements and Resources

The overall annual cost of carrying out the above science programs at both the SMT and the KP12m is approximately $2.5 million including site fees at Mt. Graham and Kitt Peak.

Resources are available as follows:

UA	$ 950 K	(principally for the SMT)
Research Corporation	$ 150 K	(to support liberal arts college faculty)
MPIfR	$ 450 K	(25% of SMT use)
Other	$ 50 K	
NSF	$ 900 K	(requested)
Total	**$2,500 K**	

The UA funds are derived principally from a State appropriation specific to the operation of the Mt. Graham International Observatory and in part from Steward Observatory resources. The Research Corporation has agreed to contribute at the rate of $150 K per year for as long as the telescopes are operational; it views its contributions as assisting astronomers at small liberal arts schools to continue with their research programs. The MPIfR funds are committed until 2004 when the MPIfR has the option of further reducing its participation. In the meantime, discussions are proceeding with several groups both in the US and overseas to acquire time at the ARO.

The ARO programs will benefit directly from the programs at the Steward Observatory Radio Astronomy Lab (SORAL) and Astrochemistry Lab, the M.I.T Haystack Observatory and University of Colorado Astronomy Department.

VI. Education and Outreach Plan

VI.1 Education Program

With the ALMA project now underway, the nation is investing heavily in the field of mm- and sub-mm-wave astronomy. In doing so it builds on the strength of both the research and educational programs carried out at university observatories. The ARO collaborators view it as essential to the future of the field that students, graduate and undergraduate, have opportunities for active participation in the technical, observational and theoretical aspects of the subject. ARO is ideally suited to this purpose.

At the undergraduate level the UA Astronomy Department currently has forty enrolled juniors and seniors, many of them as double majors in Astronomy and Physics. All are involved in research projects, several in mm/sub-mm astronomy. Most of these students (as opposed to the larger number of lower division students initially registered as Astronomy majors) will go on to graduate studies.

At the graduate level, the ARO program, even though relatively young, has produced several students that are playing important roles in this or related fields. Among them are A. Apponi (UA), J. Glenn (Colorado), G. Narayanan (UMass), C. Walker (NOAO), and C. Walker (UA). The current group of UA graduate students active in mm/sub-mm astronomy includes Chris Groppi, Christian Drouet D'Aubigny, Dewayne Halfen, Abigail Hedden, Jaime Highberger, Craig Kulesa, Chandra Savage, A. Moro-Martin. All are studying for a Ph.D. and are in good academic standing. The UA Astronomy Department requirements include courses on Atomic and Molecular

Processes, on the Interstellar Medium and on Astronomical Instrumentation. In addition there are optional seminar type courses on topics in Star Formation, Radio Astronomy and other specialists These courses are taught on a rotating basis by Bechtold, Bieging, Meyer, Rieke, Thompson, Walker and Ziurys. ARO has also assisted several external graduate students in the past. Currently, one graduate student, C. Garland (Univ. of Florida) is studying LSB galaxies with H. Butner (SO); her thesis advisor is Prof. J. Williams at the University of Florida.

Haystack, through the CMVA, has a long history of training post-doctoral researchers, graduate students and undergraduates in mmVLBI science and techniques. This URO will build on that history and emphasize the role of training students and young scientists. With both SMT and KP12m in such close proximity to the UA, there will be excellent opportunities for student technical participation at both ends of a VLBI interferometer. Haystack will welcome UA student involvement during data correlation so that students can acquire experience in all aspects of VLBI. Haystack also incorporates interferometry into numerous other educational outreach programs. Each year Haystack staff mentor four or five Research Experience for Undergraduates (REU) students in VLBI fields. Haystack staff members also teach an NSF sponsored Chautauqua course in Radio Astronomy which draws heavily on VLBI techniques and science. As part of the Small Radio Telescope (SRT) initiative, Haystack is developing an interferometer using two SRTs to develop a teaching platform for secondary schools and universities.

At the moment, the program has one post-doctoral fellow working mainly in mm/sub-mm astronomy, Michiel Hogerheijde, a Bok Fellow.

The Astronomy Department plans to continue its education program with a modest increase in numbers at all levels and with expanded opportunities for students from other departments to participate in aspects of the ARO program. Currently most of these students are from Chemistry, Electronic and Computer Engineering, Optical Sciences and Planetary Sciences.

VI.2 Outreach

Plans for outreach (all educational activities other than the formal degree programs) are extensive. Many of them involve collaborative efforts with other units or programs within Steward Observatory while others involve new efforts with the ARO collaborators or with other local astronomy organizations.

VI.2.1 Science Teacher Training

A key person in this effort is Dr. T. Slater, who has recently joined the UA Astronomy faculty and is a member of the College of Science program to train high school (and other) science teachers. Astronomy provides an excellent venue for teaching physical science, and students in this program will use the observatory facilities to gain direct experience of science in the making. Slater is also involved in direct outreach efforts with schools (K-12) in Southern Arizona, including both Tucson (Pima County) and Safford (Graham County). Slater plans to expand the current program of student and other visitors to both the KP12m site and to the SMT (and LBT, VATT) on Mt. Graham. He and his group also plan to work with eight local science teachers to develop curriculum supplements, which target science, technology and societal issues relevant to the Mt. Graham Observatory. This will involve student projects at the SMT. Similar programs are under consideration for the KP12m.

VI.2.2 Astronomy Camp

For many years Dr. Don McCarthy has conducted several astronomy camps per year, exploiting the SO facilities on Mt. Lemmon, Kitt Peak and Mt. Graham as well as at the SO Mirror Lab. These camps will include visits to and experience at the SMT and/or the KP12m depending on the duration of the camps. The ARO plans to coordinate closely with McCarthy in these programs.

VI.2.3 Undergraduate Summer School

If this proposal is funded, ARO intends to initiate a summer school in mm/sub-mm astronomy for students beginning their senior year. The program will accommodate approximately a dozen students, last for one week and involve observations at the SMT and KP12m, as well as lectures and involvement in lab activities. J. Bieging and T. Slater will run the summer school. One of the goals is to attract bright students to the field in preparation for the ALMA era.

VI.2.4 Undergraduate Observing Programs

During the last several years a group of undergraduate students coordinated by Dr. Vladimir Strelnitsky of the Maria Mitchell Observatory (MMO) and mentored by Dr. Mark Gordon (NRAO), has conducted research on variable sources such as MWC 349 using the KP12m telescope, exploiting its remote observing capabilities. This type of activity can be extended to the SMT once its new control system is in place. ARO plans to continue with the

MMO program and to make the facilities available for similar efforts with other organizations both local and elsewhere – especially at other REU sites.

VI.2.5 General Public

The SO Public Evening series offers sixteen free public lectures per year on astronomy. Results from the ARO will be featured in these public lectures, along with other topics in astronomy. The series has been offered every year since the 1930s and enjoys public audiences of well over a hundred at most lectures. In addition, the SO faculty, including those active in ARO, give talks to numerous groups, clubs, associations etc.

The Mt. Graham International Observatory, of which the SMT is part, collaborates with Discovery Park, a not-for-profit science center in Safford, in arranging public tours to the observatory. These tours are conducted by volunteer docents and include visits to the SMT control room to see observations being carried out. (They also include visits to the VATT and soon the LBT). At the moment, public visits to the KP12m are offered on an occasional basis but, if this proposal is funded, ARO intends to offer visits to the KP12m on a more regular basis, perhaps in conjunction with those organized by NOAO.

Individual groups have also conducted general outreach. H. Butner (SO) teaches basic astronomy to 60 summer students at the Governor's school for the Sciences each year. Graduate student J. Highberger has presented radio astronomy talks at local grade schools in Tucson and a local high school student participated in an internship program with L. Ziurys.

VII. Results from Prior NSF Support (past 5 years)

Peter A. Strittmatter PI

AST-02-30790:$400,000: 2002-present:"Privatization of the KP12m Telescope".

This grant was for bridge funding to keep the KP12m in operation following NRAO's closure. Below are some of the published results that have come from the KP12m over the past year.

1.Pagani, L, Gallego, A. T., & Apponi, A. J., 2001, "On the Frequency of the CS (J:2$\rightarrow$1) and (J:5$\rightarrow$4) transitions", A&A, 380, 384.

2. Halfen, D. T, Apponi, A. J., & Ziurys, L. M., 2001, "Evaluating the NO Chemical Network Distribution of N_2O and NO in the SgrB2 Complex", Ap. J., 561, 244.

3. Turner, B. E. & Apponi, A. J., 2001, "Microwave Detection of Interstellar Vinyl Alcohol", Ap. J., 561, L207.

4. Highberger, J. L., Savage, C., Ziurys, L. M., & Bieging, J. H., 2001, "Heavy Metal Chemistry in Protoplanetary Nebulae: Detection of MgNC, NaCN, and AlF Towards CRL 2688", Ap. J., 562, 790.

5. Lubowich, D. A., Pasachoff, J. M., & Ostenson, J. A., 2001, "Deuterium near and far in the Galaxy", in *Cosmic Evolution*, Ed. E. Vangioni-Flam, R. Ferlet, and M. Lemoine (New Jersey: World Scientific), p. 63.

6. Gordon, M. A., Holder, B. P., Jisonna, L. J., Jorgenson, R. A., & Strelnitski, V. S., 2001, "3 year Monitoring of Millimeter Wave Radio Recombination Lines from MWC 349", Ap. J., 559, 402.

7. Bockelee-Morvan, D. et al., 2001, "Outgassing Behavior and Composition of Comet C/1999 S4 (LINEAR) During its Disruption", Science, 292, 1399.

8. Savage, C., Apponi, A. J., Ziurys, L. M., & Wyckoff, S., 2002, "Galactic $^{12}C/^{13}C$ Ratios from Millimeter Wave Observations of Interstellar CN", Ap. J., in press.

Lucy M. Ziurys Co-PI

AST-98-20576: $234,751: 1999-2002: "Studies of Interstellar/Circumstellar Molecules: From the Laboratory to AGB Star".

This grant provided funding for both lab studies and observation of refractory circumstellar molecules. Some representative publications are listed.

1. Sheridan, P. M., Brewster, M. A., &. Ziurys, L. M, 2002, "Rotational Rest Frequencies for CrO and CrN", Ap. J., in press.

2. Sheridan, P. M, Xin, J., Ziurys, L. M, Beaton, S. A, Kermode, S. H., & Brown, J. M., 2002, "The Pure Rotational Spectrum of NaC in its X4S- State: Observation and Interpretation", JCP, 116, 5544.

3. Bieging, J. H., & Ziurys, L. M, 2001, "Heavy Metal Chemistry in Protoplanetary Nebulae: Detection of MgNC, NaCN and AlF Towards CRL 2688", Ap. J., 562, 790.

4. Brewster, M. A., & Ziurys, L. M, 2001, "The Millimeterwave Spectrum of NiC (X1S) and CoC (X2S+)", Ap. J., 559, L163.

5. Ziurys, L. M, Savage, C. S., Highberger, J.L., Apponi, A. J., Guélin, M., & Cernicharo, J., 2002, "More Metal Cyanide Species: Detection of AlNC Towards IRC+10216", Ap. J., 564, L45.

John H. Bieging Co-PI

AST-96-18523: $118,250: 1997-2001: "Mm-Wave and MidIR Studies of Stellar Mass Loss from the AGB to the Planetary Nebula".

This funding was used to carry out molecular spectroscopy and mm/midIR imaging of circumstellar envelops of AGB stars evolving to planetary nebula. Some representative publications are listed.

1. Bieging, J.H., Knee, L.B.G., Latter, W.B., and Olofsson, H. 1998, "Molecular LineObservations of Southern S Stars", A & A, 339, 811

2. Dayal, A., Hoffmann, W.F., Bieging, J.H., Hora, J.L., Deutsch, L.K.,and Fazio, G.G.1998, "Mid-Infrared (8 - 21 micron) Imaging of Proto-Planetary Nebulae", AstrophysicalJournal, 492, 603

3. Bieging, J.H., Shaked, S., and Gensheimer, P.D. 2000, "Sub-mm- and mm-wavelength Observations of SiO and HCN in Circumstellar Envelopes of AGB Stars", Ap. J., 543, 897

4. Bieging, J.H. 2001, "Discovery of Two New HCN Maser Lines in Five Carbon Stars", Ap. J., 549, L125

5. Bieging, J.H., and Wilson, C.D. 2001, "High Resolution Images of CO J=2-1 Emission from the Carbon Star V Cyg", AJ, 122, 979

6. Bieging, J.H., Rieke, M.J., and Rieke, G.H. 2002, "CO 1st Overtone Spectra of Cool Evolved Stars: Diagnostics for Hydrodynamic Atmosphere Models", A&A, 384, 965

Sheperd Doeleman Co-PI

AST-9727353: $1,628,000: 1998-2001: "Astronomical Research and Technical Support of Mm-VLBI".

Much of the foundation for the high frequency VLBI work proposed in this URO was done during the AST-9727353 grant which funded the Coordinated MM VLBI Array (CMVA). Progress on key science drivers including determining the structure of SgrA* at the center of our Galaxy and mapping SiO masers in envelopes of both evolved and forming stars was made using VLBI at 3 mm wavelengths.

1. Conway, J.E., "VLBI spectral absorption in AGN", New Astronomy Reviews, 43(8), 509.

2. Doeleman, S, Lonsdale, C and Greenhill, L., "VLBI Imaging of the 86 GHz SiO Maser Emission in the Circumstellar Envelope of VX Sgr", ApJ, 494, 400, 1998.

3. Doeleman, S.S., Shen, Z.Q., Rogers, A.E.E., Bower, G.C., Wright, M.C.H., Zhao, J.H., Backer, D.C., Crowley, J.W., Freund, R.W., Ho, P.T.P., Lo, K.Y., Woody, D.P. 2001, "Structure of Sgr A* at 86 GHz using VLBI Closure Quantities," AJ, 121, 2610.

4. Krichbaum, T.P., Graham, D.A., Witzel, A., Greve, A., Wink, J.E., Grewing, M., Colmer, F., de Vicente, P., Gomez-Gonzalez, J., Baudry, A., Zensus, J.A., "VLBI Observations of the Galactic Center Source SgrA* at 86 GHz and 215 GHz", A&A, 335, L106.

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This research netted a rich harvest of results including the characterization of irradiated outflows, the first complete assay of visual wavelength shocks and protostellar outflows in entire giant molecular clouds, and evidence that multiple star systems play fundamental roles in regulating accretion onto young stars, triggering major outflow episodes, and in determining the final stellar mass.

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