The Cradle of Life: Imaging Galactic Chemistry

Many Pixel/Practical-N/Large-Diameter Telescope Concept

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The next decade holds rich opportunities for advances in understanding the chemical processes in space, which may have led to life on Earth (e.g. Cheba and Hand 2005, Annu. Rev. Astron. Astrophys. 2005. 43:31–74, Kwok, 2009, Astrophys. Space Sci., 319, 5). When the proper technological development priorities are set, along with wise choices in laboratory chemistry, the next decade will be pivotal in mankind's understanding of the beginnings of life on Earth.

Historically, large single-dish telescopes have led the way in discovering new molecules in the interstellar medium. Why is this? Until recently, only single dish telescopes have had sufficient spectral resolution required for discovery of new molecules. In addition the molecules form over large regions, so that single dish telescopes have sufficient angular resolution for discovery observations.

The future generations of radio telescope arrays must have sufficient sensitivity and spectral bandwidth to meet the challenges required for discovery of new molecules. How should we prioritize our technological developments for searches for new molecules in the next decade? What are the technical aspects of the next generation of instruments? We present a concept for an interferometer, to be developed in the next decade, to achieve the optimum sensitivity and spectral resolution for study of galactic chemistry.

Introduction

Fundamental to the quest for high sensitivity is building either very large telescopes or extremely many (> 1000) small antennas in an array. We propose an optimum configuration for spectral line mapping, by building an interferometer between a large telescope and a number of small antennas. To match the field of view of the small antennas, *focal plane arrays* (FPAs) are required on the large antenna.

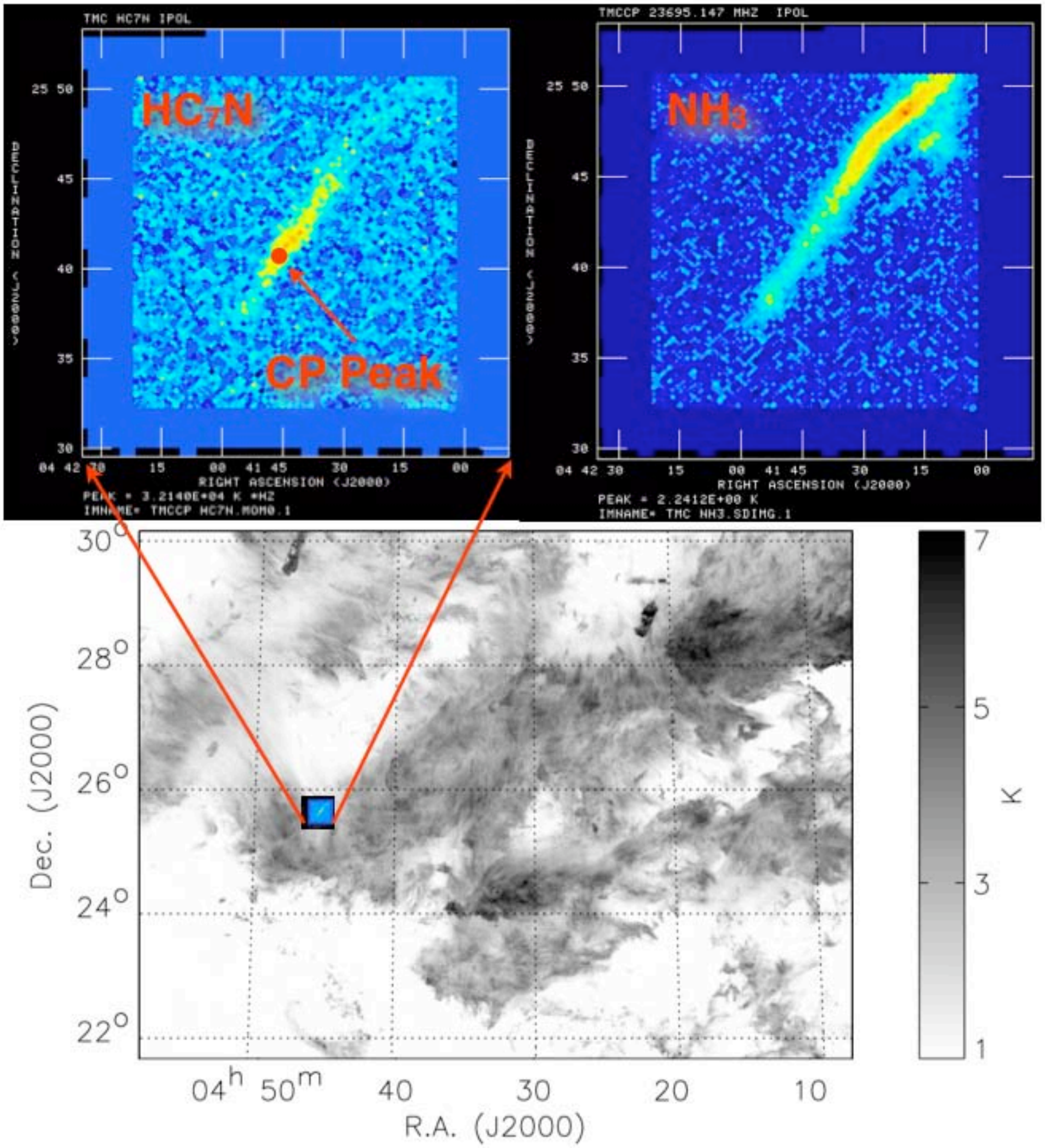

Figure 1: Grayscale CO molecule image of TMC from Goldsmith et al. (2008), with GBT images of a small region containing larger molecules. The upper left image is the distribution of HC_7N and at left is the ammonia emission in the same region. The upper images show data from the GBT 18-26 GHz prototype of a 7-pixel array. The red dot in the left image is the location of the Cyanopolyyne Peak (Langston et al 2009, https://safe.nrao.edu/wiki/bin/view/Kbandfpa/)

This FPA interferometer meets the sensitivity requirement for galactic mapping projects and reduces the total cost of the project.

We present an example science observation to motivate the technology developments. Figure 1 shows recent observations of the Taurus Molecular Cloud (TMC) by Goldsmith et al. (2008, Ap. J., 680, 428). The grey scale image shows the large region containing CO emission, which is the strongest molecular line. The grey scale image was produced using the Sequoia 32 pixel focal plane array on the 13.7m Quabbin millimeter telescope. The color images of the Cyanopolyyne peak (CP) in TMC show molecules HC_7N and ammonia (NH_3) are found in filaments. The Robert C. Byrd Green Bank Telescope (GBT) images were produced with the prototype pixel of a 7 pixel, 18 to 26 GHz bandwidth focal plane array under development.

The TMC CP region has been the target for several hundred hours of GBT observations, which have resulted in recent discoveries of new molecules (e.g. Hollis, J. M et al, 2004, Ap. J. 610, 21, Lovas et al. 2006, Ap. J., 637, 37, Langston and Turner, 2007, Ap. J. 658, 455, Remijan et al. 2008, Ap. J. 675, 85, Thaddeus, P et al. 2008, Ap. J., 677, 1132). These observations were made over the frequency range 7 to 49 GHz. During these observations only a single location was studied. All other emission in the field was missed. The need for larger field of view images is clear from Figure 1.

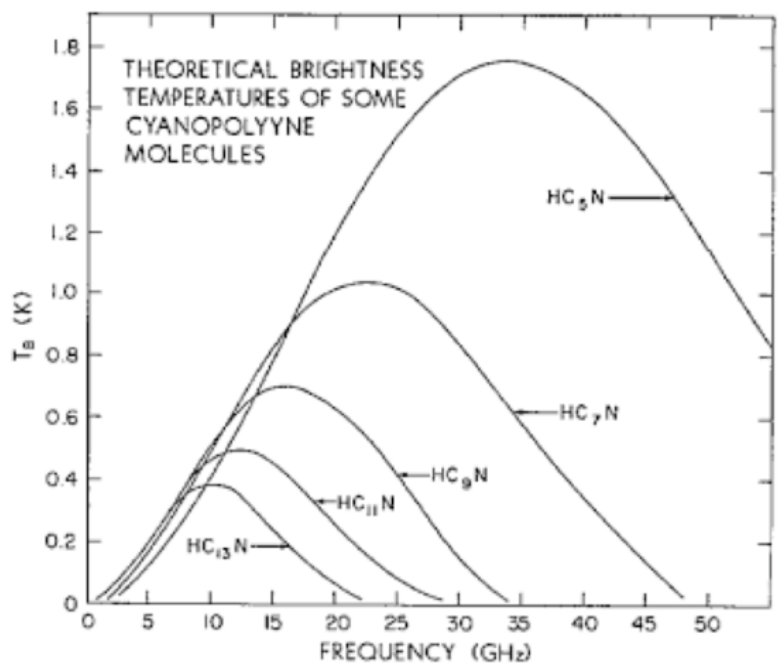

Figure 2, from Bell et al. 1997, Ap. J. 483, L61, shows a model for the line intensity versus observing frequency. The model assumes the same abundance of each species and predicts a decrease in intensities for larger molecules. The figure also shows the frequency of peak emission decreases as the molecule size increases.

The GBT is 100m in diameter. In Figure 1 the size of the GBT beam at 23 GHz is shown by the red dot at the location of the Cyanopolyyne peak (CP), indicating the field of view of a single pixel image is too small for observations of this field. The size of the interferometer antennas must be chosen to match the field of view of the FPA. Due to the extended nature of the chemical processes, observations are required with a many pixel receiver on a large telescope or observations with small interferometer antennas with large field of view.

The optimum frequency of observation of large molecules will be different than the frequency of studying small molecules. The frequency range from 5 to 115 GHz contains many important clues to the study of pre-biotic chemistry. The lesson to be taken from Figure 2 is that *if the goal is studying the formation of large molecules, the optimum observing frequency is lower than for observing small molecules.*

To date, new molecules have been *discovered* at only 34 sites in our galaxy (Lovas, 2008, http://physics.nist.gov/cgi-bin/micro/table5/start.pl). Why only 34? Large telescopes have small fields of view, so deep surveys take a very long time. There are so few sites of new molecule discoveries because much of our galaxy remains unexplored. Small array antennas hold the promise of new sites of discovery, since they have larger fields of view. However, to date only one molecule, acetic acid, has been first detected with a telescope array (Mehringer et al. 1997, Ap J, 480. 71). Discovery of molecules with interferometers will be more promising by increasing the sensitivity and spectral resolution of the new array configurations.

How to proceed in the Next Decade

The discovery of larger, more relevant, pre-biotic molecules is hampered by the extremely weak signals expected. The fundamental problem is doubling the spectral complexity of a molecule (doubling the number of lines per unit bandwidth) increases the time to detect each transition by a factor of 4. Partially this factor of observing time can be deduced by simultaneously observing several transitions (e.g. Hewitt, J.W. et al., Ap. J. 652, 1288). If the emission is too weak for detection of a single molecular species, classes of molecules may be discovered if a good model is available for the relationship between line intensities and many transitions fall within the observing band (e.g. Langston and Turner 2007).

So, in general, observing sensitivity to detect molecule of mass, M, will require an improvement in sensitivity by a factor between M and M^2. The observing sensitivity can be increased by 1) increasing the telescope area, 2) reducing the system temperature, 3) increasing the number of transitions observed simultaneously and 4) increasing the number of regions simultaneously observed. A factor of 100 improvement in sensitivity and angular resolution should increase the number of detected molecules from the current 150 (March 2009) to over 1000. This will lead to a dramatic increase in our understanding of the chemistry that led to life on earth.

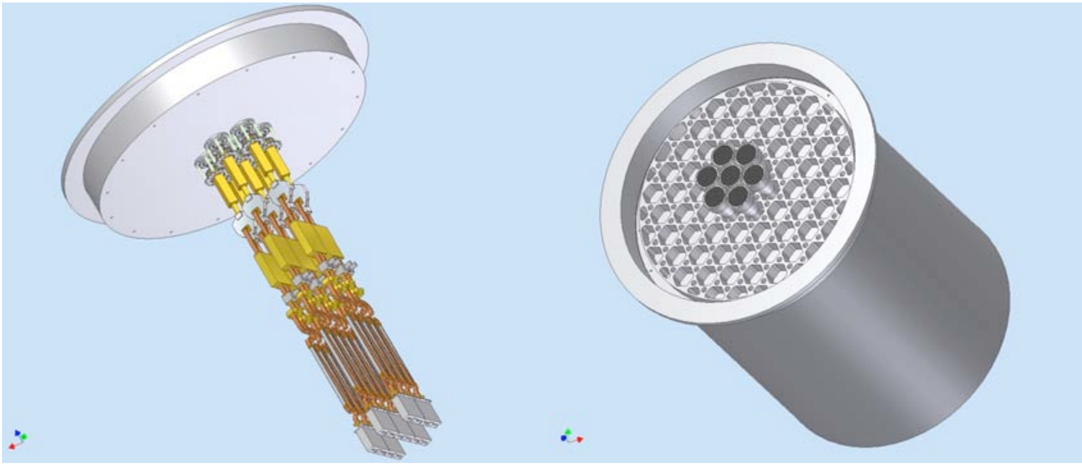

Figure 3: Configuration of the 7 pixel FPA for the GBT at 18 to 26 GHz. Left shows the components internal to the cryogenic Dewar. Right shows the feed horn configuration for the 61 pixel array, with the inner 7 pixels populated. (S. White et al 2009, https://safe.nrao.edu/wiki/bin/view/Kbandfpa)

The technology of radio astronomy receivers is mature, so that only a fairly small gain in reduced system temperature can be expected, compared to the current receivers. Recent improvements in receiver bandwidth have increased the number of spectral lines that can be simultaneously observed. However the detector (spectrometer) bandwidth has not yet matched the available observing bandwidth. The U.C. Berkeley Center for Astronomy Signal Processing and Electronics Research (CASPER, casper.berkeley.edu) developments for the Allen Telescope Array (ATA), the EVLA and the GBT are good strides towards complete spectral coverage of the observing bands. These development efforts must continue in the next decade.

The success of the Sequoia focal plane array for imaging large regions with good sensitivity and high spectral resolution clearly indicates that this group should continue developing large format focal plane arrays for sub-millimeter, millimeter and centimeter wavelengths.

In the next decade, for studies of interstellar chemistry, the NRAO should complete the large, 61 pixel, 18 to 26 GHz focal plane array and the 100 pixel, 75 to 115 GHz, focal plane arrays, as well other focal plane array instruments.

The technologies for the reconfigurable correlator being developed by the CASPER/Allen Telescope Array project are critical for astrochemical studies over large angular regions.

The way forward for astro-chemistry in the next decade is clear, build array receivers (e.g. Figure 3). Near the end of the next decade, we will be in a position to achieve a factor of 60 sensitivity improvements in mapping sensitivity compared to the current GBT capabilities. Because astro-chemistry occurs in a vast variety of size scales, from AUs to 100s of parsecs, the science goals require improved angular resolution. To increase the angular resolution of the GBT and increase sensitivity, we propose the Green Bank Array (GBA), shown schematically in Figure 4.

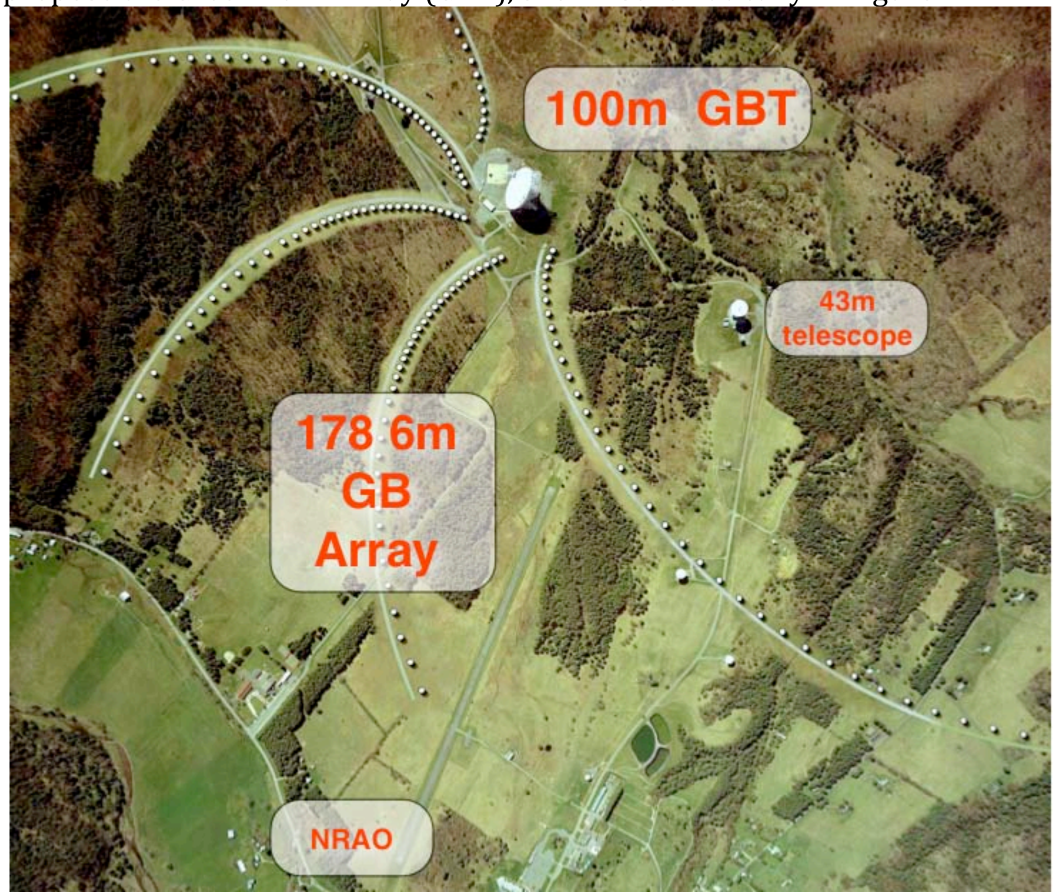

Figure 4: Configuration of an array of 6m diameter telescopes within a 1 km radius of the GBT, to yield a high sensitivity array with 10 times the GBT angular resolution.

Green Bank Array

We take as a valuable and achievable goal: *reaching the sensitivity of a kilometer diameter telescope for mapping galactic chemistry, and a factor of 10 in angular resolution, compared with the current capabilities*. This goal can be achieved by building on the technological steps of the first part of the next decade. By the middle of the next decade, the EVLA and ATA correlator development efforts should near completion. The ALMA array will be in operation and the GBA will provide the high sensitivity, higher angular resolution to contribute to the ALMA science goals. The Green Bank Array (GBA, http://www.gb.nrao.edu/gba) will be the world's most sensitive instrument for the discovery of new molecules and deducing the chemical processes in the interstellar medium.

Approach and Costs

An optimum approach to simultaneously increase GBT mapping speed by a factor of 100 and increase the angular resolution by a factor of 10 is by deploying an interferometer array of small antennas within 1 km of GBT. This approach is optimum for large field of view mapping, by building on existing capabilities.

We assume a completed 61 Pixel, 18 to 26 GHz, FPA (Figure 3) with instantaneous field of view 3x8x20" = 8'. This angular diameter should be matched to the beam size of the array antennas. At 23 GHz, a 6m-diameter telescope has a 9' field of view. This is approximately the size of antenna utilized by the ATA (http://www.seti.org/ata). For a 100 pixel, 75 to 115 GHz array, the field of FPA view is diameter is 3'. A 4m-diameter telescope has a 3' beam diameter at 100 GHz.

Increasing the GBT mapping speed is achieved primarily by increasing the number of pixels. Increasing the angular resolution implies building an interferometer. Figure 4 shows a configuration that achieves approximately 1000m diameter telescope sensitivity, using N 6m diameter telescopes, in conjunction with a 61 pixel FPA. Remember that the sensitivity of a baseline of an interferometer is proportional to the geometric mean of the areas of the two telescopes. For a 6m and 100m pair of antennas, the geometric mean is ~25m. By placing many small antennas near the GBT, we can readily fill the "visibility plane", yielding good imaging capabilities.

The number of 6m telescopes required to yield the same mapping speed of a 1000m diameter, single pixel, telescope is deduced in the equation below:

$$(6^2\ m^2\ N + 100^2\ m^2) \times 61 = 1000^2\ m^2$$

Solving for N yields 178. The collecting area of 178 6m-diameter antennas corresponds to $178^{1/2} \times 6$ m = 80m diameter equivalent telescope. Placing these antennas on arcs radiating from the GBT results in a configuration shown in Figure 4. The arc configuration was chosen to simplify fiber optics connections and the power distribution network. The correlation of signals will only be between the individual pixels of the GBT FPA and the 6m dishes, not between the 6m dishes themselves, in order to keep the cost of the correlator manageable.

Imaging Capabilities

The ability of an interferometer to produce good images of regions depends on good calibration and fully sampling the visibility plane, that is, the measurements of the Fourier transform of the sky brightness. We consider the capabilities of the proposed array by comparison of its parameters with existing facilities. The number of instantaneous baselines is an important parameter. For the VLBA array of ten 25m-diameter dishes, the number of instantaneous baselines is 10*9/2 = 45.

For the EVLA, the number of baselines is 27*26/2 = 351. For the GBA, there will be 178 baselines to each pixel of the array, so will yield similar sensitivity to the EVLA. GBA observations must be scheduled so that earth rotation of the array yields a good distribution of baselines. The typical mapping mode observation would scan the region of interest over an interval, followed by a repeated observation after the projected baselines had rotated into an optimum configuration.

The sensitivity of the 6m to 100m antenna baselines is slightly superior to EVLA baseline sensitivity, due to the excellent performance of the GBT at 18 to 26 GHz. In addition, the total number of baselines is the product of the number of pixels to the number of 6m antennas, so the instantaneous number of baselines is 10,858; more than an order of magnitude larger than that of the EVLA. The number of baselines is much smaller than for the full ATA or SKA designs.

Calibration of radio wavelength observations is accomplished by measurement of the amplitude and phase of the gains of individual antennas, assuming a model for the brightness distribution of the calibration source. This is possible because there are many more baselines than antennas. For the EVLA, there are 27 antenna gains and 351 baselines, so the gains are over determined by a factor of 351/27 = 13. In the GBA case, there will not normally be cross correlations between 6m antennas, but there will be many cross correlations between pixels of the focal plane array. The number of unknown complex gains is (178+61) = 239. The ratio of baselines to unknowns is 10,858/239 = ~45.

The EVLA and the GBA calibration techniques will be different, because the 61 pixels will be observing different locations on the sky, but the amplitudes and gains are still simultaneously constrained. In the GBA case, the majority of the least squares minimization of the antenna-based gains will be done assuming there is no emission in the majority of the fields. Alternately, during calibration observations with the GBA, we could perform 6m to 6m antenna cross correlations to determine the gains. These calibrations could be applied during the mapping observations.

We request encouragement from decadal review committee for support to study in detail the GBA concept, then document observing modes and calibration requirements.

Cost Estimate

The GB Array concept needs further study before a solid cost estimate can be provided. We also look forward to learning from the successful completion of the ATA, EVLA and GBT FPA programs. We will build our detailed cost estimates, based on their experience. Here we present only rough estimates to guide in planning.

The ATA group has solid experience with their 6m diameter antennas, although they are not yet outfitted to operate at 18 to 26 GHz. The ATA project has successfully built cryogenically cooled receiver systems, along with power distribution, digital data sampling and computing facilities for a cost of $188,000 per antenna. We estimate that wideband receiver system for 18 to 26 GHz would cost more, and we require a minimum of 2 GHz observing bandwidth. The additional bandwidth adds to the cost per antenna, but more significantly adds to the correlation system cost.

Including 10 % contingency, we assume a cost of $250,000 per antenna. The cost of 178 fully outfitted 6m antennas is $44.5M.

Concerning the correlation, the number of simultaneously correlated baselines is large, 61 x 178 = 10,858 baselines. The number of polarizations and spectral bands scales the total number of baseline pairs. The CASPER correlator collaboration uses the upgraded "Roach2" board and with this COTS hardware they can share the firmware design with other projects. Extrapolating from the CASPER correlator collaboration costs estimates, we find that the GBA correlator would cost $1.5M per 350 MHz band. Our minimum simultaneous bandwidth is 2 GHz, so yields a total correlation cost of $8.6M.

After constructing the array, significant costs are associated with data processing, and archiving. For the purposes of this rough estimate, we adopt a 10 % overhead for management and other related activities or $5.3M. The appropriate annual operations budget for a construction project is approximately 10% of the construction total, or $5.8M per year.

These cost estimates are large, but are more than an order of magnitude lower than other proposals to achieve the same spectral line mapping sensitivity.

Development and Expansion

Before construction of the full GBA, it is prudent to test the components and configuration. A reasonable start is construction of a 20 element array, yielding 190 baselines between the 6m antennas and 20x61 = 1201 baselines between the antennas and the FPA, in a 1 GHz band. The cost of this development is $5M for the antennas, $0.5M for the correlator and $2.0M for associated overhead and contingency.

Once the infrastructure for FPAs and arrays of antennas is in place, the expansion to other frequency ranges is possible. The design of the 18 to 26 GHz system for the 6m antennas should include a plan for expansion to other frequency ranges. These design efforts will be performed collaboration with other university groups. During the prototyping phase we must address the imaging techniques required for combing the separate FPA beams observations into images. All groups designing high sensitivity imaging arrays share these technical challenges.

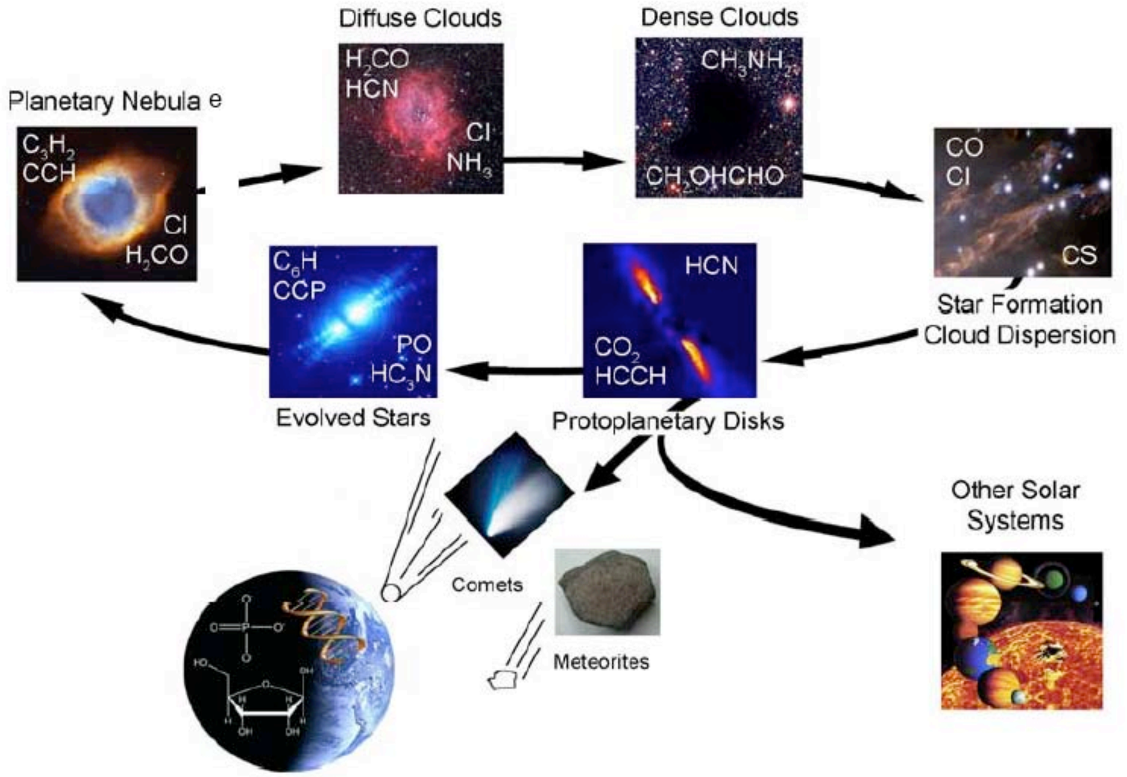

Figure 5: Many astrophysical processes exhibit rich chemical structures. A telescope dedicated to discovery and imaging chemical signatures is a priority for the science goals of the next decade. Image is from Ziurys (2009, Astro2010 white paper).

Conclusion

We have the opportunity in the next decade to make major advances in our understanding of the pre-biotic chemistry that led to life on Earth. Many of the science priorities expressed to decadal review committee concern galactic chemical processes (e.g. Figure 5; Boss et al., Heiles et al., Meier, et al., Sandford et al., Yun et al., Ziurys et al., Astro 2010 science white papers). The decadal review panel should strongly support the technological advances that lead to achieving that goal. These technologies were invented in the current decade and are ready for full-scale deployment in the next. The decadal review committee should support the open hardware and firmware efforts that are already bearing fruit in the form of new capabilities for astronomy.

The arrays of receivers and arrays of antennas are the technology to increase our sensitivity to chemical processes in the galaxy. The decade review panel should encourage research and design efforts early in the next decade. These technologies can be demonstrated with the existing National Science Foundation facilities in Green Bank, WV. Sharing design and construction efforts with many university collaborations is a core part of the development plan.