Astrobiology and SETI

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"Are we alone?" "Where did we come from?" These are the defining questions of the new field of Astrobiology, and they are also the questions that have tantalized humanity throughout recorded history. The SKA will afford an excellent opportunity to answer these old questions and thereby calibrate our place in the cosmos. With the SKA we may discover another technological species and chart the pathways by which complex organic molecules assembled in interstellar space were incorporated into, or reassembled within, nascent planetary systems and the role these molecules play in creating habitable worlds.

1. Introduction

Today we know of more than 100 planetary systems surrounding nearby stars. None so far are exactly like our own Solar System. The closest analogy is the 55 Cancri system with a 4 Jupiter-mass planet in a fairly-low eccentricity orbit at 5.5 AU, plus an additional massive planet in a 0.11 AU orbit (Marcy et al., 2002). Radial velocity data suggest that solar-type stars with a metallicity about 1/3 solar form orbiting giant planets about 3% of the time, with the percentage rising to about 20% if the metallicity is 3 times solar (Fischer et al., 2004). The mass distribution of the detected planets is steeply rising towards the low mass limit of this technique, implying that planets less massive than Saturn should be plentiful. A recent ESO press release (ESO press release, 2004) claims the detection of a planet with 14 Earth-masses around the star mu Arae. Earth-like planets remain out of reach for the moment, but the Kepler spacecraft scheduled for launch in 2007 should yield statistical information on the frequency of terrestrial-size planets with periods less than about a year before the end of the decade (Koch et al., 2004). An optical choronographic spacecraft and a free-flying array of nulling IR interferometers will attempt to image terrestrial planets in the habitable zones of a few dozen nearby stars towards the end of the next decade, and to conduct a chemical assay for biosignatures within the atmospheres of any such planets detected. Atmospheric absorption lines of water and oxygen (between 0.5 and 0.8 μm) or water, carbon dioxide and ozone (between 6.5 and 13 μm) may permit the inference of biology on these newly-imaged planetary surfaces (Beichman, 2004). As the SKA begins its operational life, we should know a great deal more about the prevalence of habitable worlds in our immediate vicinity and be on the verge of remotely sensing the disequilibrium chemical by-products of any life-as-we-know-it, but in the absence of successful results from ongoing SETI projects, we will not yet have formulated a compelling answer to the "Are we alone?" question. Using the SKA to find habitable worlds by detecting the technological activity of the inhabitants could change all that.

2. SETI

2.1. Signal Characteristics

There is no general agreement about the best frequency at which to search for deliberately broadcast signals from a distant, advanced technological civilization, nor is there any single characteristic that is necessary and sufficient to identify such signals. For deliberate transmissions, it is possible to use the properties of the interstellar medium through which they must propagate, the nature of the astrophysical backgrounds against which they must be detected, physics as we currently understand it (including the uncertainty principle), and our own short-lived experience with technology to establish some plausible categories of signals and set constraints on realistic searches [see the detailed deliberations in *SETI 2020* (Ekers et al., 2002)].

An intentional beacon might imitate the characteristics of a natural astrophysical emitter (but with some detectable difference in detail) so that an emergent technology would capture the signal with receivers invented to study the universe. Or, in the other extreme, beacon signals might have characteristics that are an unmistakable hallmark of technology, e.g. extreme compression in the frequency and/or time domains approaching the limit of $B\tau = 1$, or modulation of the angular momentum of 'twisted light'. Searches for such signals began at centimeter wavelengths in 1960, and since then there have been over a hundred different search projects that are cataloged[1], the most recent of which are searches for nanosecond, broadband, optical laser pulses. For low-loss, long distance propagation through the galaxy, and low background noise, the terrestrial microwave window from 1 to 10 GHz remains attractive and is still largely unexplored after decades of searches. This is not surprising since the 'Cosmic Haystack' is vast and at least nine-dimensional (3-space, 1-time, 1-frequency, 2-polarization, 1-modulation, 1-transmitted power). Although individual searches must be delineated by some specific hypothesis and explore some small subset of this haystack, SETI researchers in general take the long view, and continuously plan for future improvements and innovations. Because of its great sensitivity, large field(s) of view, and multiple phased-array beams the SKA will be a superb instrument for SETI searches of the future. Computational limitations currently restrict microwave searches to narrowband continuous wave signals, or narrowband, long-duration pulses (to avoid the necessity of searching through dispersion measure if the signals have not been predispersed at the source), but in the era of the SKA, more complex pattern recognition may also be affordable, and the flexibility of a multi-user facility may provide as-yet-unrecognized opportunities for commensal searching. We should plan for the necessity of a great deal of special-purpose signal processing capacity (either dedicated hardware or reprogrammable CPUs) in order to conduct efficient searches over 9 GHz of the spectrum within the terrestrial microwave window using sub-Hz resolution. For the time being, Moore's Law is on our side.

For unintentional, or leakage, signals or for manifestations of extraterrestrial astroengineering projects, it isn't possible to satisfactorily constrain the search problem, and the best strategy for detection will be a vigorous exploration of the astrophysical universe with an open mind. The SKA is designed, in part, to permit access to previously unexplored 'discovery space' and in that way it may prove to be an ideal detector of alien technologies.

2.2. SETI Targets

Historically there have been two search modalities for SETI; targeted searches (primarily of solar-type stars), and sky surveys. These search strategies optimize for the detection of different classes of signal (weak and nearby versus intrinsically strong and distant) and to the extent possible, both should be pursued. Simplistic arguments to determine the relative efficacy of these two approaches based on the assumption of a power law distribution for extraterrestrial transmitter powers (Drake 1973) have remained unconvincing in the absence of any method of constraining the range of values for the exponent. More recently, Dreher (2004) has argued that a δ-function is perhaps a better model than a power law for the distribution of parameters characterizing deliberately engineered products. In practical terms, the crossover between targeted and survey strategies occurs when the number of targets exceeds the gain of the antenna.

In the case of the SKA, with a 1 degree (6 arcmin) field of view at 1 GHz (10 GHz) and a large number of phased-array beams (nominally 50) whose FWHM will be determined by the largest baseline selected for inclusion in the observations, it is a bit more difficult to decide where this break occurs and therefore how to size a targeted observing program. The number of targets will greatly exceed the gain of the primary elements, but when the majority of elements in

[1] www.seti.org/seti/seti_background/archive/Welcome.html

the array are used, the 50 phased-array beams sparsely fill the field of view, and the number of targets could be much less than gain of the array. Assuming the SKA will have access to 80% of the sky from whichever site is chosen, on average, a target list of 1.7 million (1.7×10^8) stars would provide 50 stellar targets per primary field of view at 1 (10) GHz. Today the best stellar target catalog contains about 250,000 stars (Turnbull & Tarter 2003), but in the epoch of the SKA, the Gaia spacecraft should have provided distance measurements for a billion stars, as many as 10% of which might be considered good targets on the basis of what we continue to learn about the statistics of habitable worlds.

Having no credible a priori way to limit the number of stellar targets that must be searched for a significant SETI effort, it is reasonable to adopt this foreseeable limit in cataloged targets of $\sim 10^8$ stars as a goal. There will be a factor of 10 difference in the stellar density from galactic plane to pole in a magnitude limited catalog. For increased efficiency, observations are likely to be biased towards the plane. At least 9 GHz of spectrum must be analyzed for narrowband signals. If the SKA is implemented with ultrawideband frequency receivers, it is quite probable that the observations will be conducted by multiplexing many observing frequency bands on fewer target stars at one time; perhaps 10 bands on each of 5 stars to use the 50 phased-array beams efficiently. The Allen Telescope Array (DeBoer 2004) will soon provide some experience with this type of flexible, resource-optimized observing strategies for SETI in a shared radio astronomy context. Today, targeted searches typically spend a few minutes observing each target at each frequency with close to a factor of two in overhead for follow-up and RFI mitigation. If we take 5 minutes as the nominal observing time and 10^8 stars as the goal, how long will it take to complete the observations of the terrestrial microwave window using 50 phased-array beams and signal processing systems capable of processing 1 GHz of bandwidth? The daunting answer is nearly 200 years, and this doesn't even for allow multiple observations to accommodate time-varying or scintillating signals.

2.3. Sizing The Search

There are three obvious ways to improve this time requirement, one of these is clearly possible: cut down the number of targets or the frequency range to be searched (unless there really is some 'magic' numerology that favors certain frequencies, these are equivalent strategies). The other two options for speeding up the search may not be feasible or affordable, depending on the direction and pace of technological improvements in the coming decade. Increasing the number of phased beams by a factor of 100 (and the amount of SETI signal processing equipment as well) is a straightforward extrapolation from current capabilities, but it remains to be seen if it is affordable. Also, for SKA designs with limited fields of view, it may not be possible to use all beams efficiently. Enhancing the performance of the imaging correlator that is the central processing engine for most of the science envisioned for the SKA is another option. In essence what is required is a three-dimensional Fourier transform device where the last spectrum-forming transform is large enough to yield the ultrafine (sub-Hz) resolution required by SETI. This then permits an extremely sensitive survey in lieu of a targeted search. Current correlator architectures that allow tradeoffs of bandwidth for channel resolution are inadequate because of the desire to cover the entire 1-10 GHz window. Such a 3-D FFT architecture has been implemented on a small scale for a 64-element transit array on a rooftop in Tokyo. Since there is already concern that it may not be possible to construct a correlator that can achieve high spatial resolution imaging over the full field of view for the 'Large-N' design concepts for the SKA, using only a modest number of spectral resolution channels, this option seems unlikely to be available for SETI searches unless commercial and military pressures push computational architectures in unexpected directions.

2.4. Searching Several Million Stars To 1000 Light Years

At first glance, reducing the number of targets seems like the wrong way to proceed, but it is a realistic fallback if the optimistic predictions about too-cheap-to-meter processing costs fail to materialize. Because beam forming at remote stations reduces the field of view, SETI observations will use only the 75% of the collecting area envisioned to be within 150 km of the core. Table 1 assumes a detection threshold for narrowband signals of 1×10^{-28} W/m^2, two orders of magnitude improvement over current searches. This is the sort of sensitivity that is consistent with minutes of observation per target, and millions (as opposed to hundreds of millions) of targets, over a few years of telescope time, assuming that the signal processing remains comparable to what has been done to date. The left hand column of the table lists the effective isotropic radiated power from a number of representative terrestrial technologies. Subsequent columns provide the actual transmitter power and the typical gains of the transmitting antenna, the distance in light years that such a signal would be detectable using the SKA, and the total number of stars within range.

But it is likely that computational capacity will be too-cheap-to-meter and thus the previous assumptions about signal processing are overly pessimistic, as they assume no signal processing gain beyond what is now possible and no new algorithms for other categories of signals. Twelve years hence, Moore's law implies a cost-neutral improvement by a factor of 256. It appears quite reasonable to use the enhancement in processing power to both increase the number of phased-array beams by an order of magnitude above the 50 assumed (thus extending the time per observation and improving sensitivity by a factor of 3), and to narrow the frequency channel width by an order of magnitude for another factor of 3 improvement in sensitivity. Note that interstellar multi-path scattering will broaden an intrinsically coherent signal, so 0.01 Hz is a practical lower limit for channel resolution. The bracketed numbers in the last two columns of Table 1 show the results for a detection threshold of 10^{-29} W/m^2. A targeted search of a few million stars will explore most of the good targets out to about 1000 light years from Earth for a range of transmitter powers that are prevalent in our own 21^{st} century technology.

3. Astrobiology

3.1. The Building Blocks Of Life

Even if the SKA does not succeed in answering the "Are we alone?" question, it will do an excellent job at helping us to understand "Where did we come from?" The chemistry of molecular clouds that serve as stellar nurseries is overwhelmingly organic. Much has been made of the apparent direct connection between this chemistry and the inventory of prebiotic chemical building blocks available to participate in the origin of life on the early Earth. In this regard, the claimed detection of glycine in hot cores of high mass star formation regions (Kuan et al., 2003), and the slight excess measured for the L-enantiomer over the D-form in abiotic amino acids within the Muchison and Murray meteorites (Pissarello & Cronin, 2000) particularly invite this interstellar connection to the origin of life as we know it. Many of the studies of star forming regions have been carried out at IR, (sub)mm, and mm frequencies. At these frequencies spectra of large complex organic molecules suffer from line confusion. At cm wavelengths, the molecular signatures will be much cleaner. Lacking the sensitivity and spatial resolution of the SKA, it hasn't been possible to distinguish between poetic inferences and plausible pathways for exogenous delivery of prebiotic molecules to nascent planets. Dust grains appear to provide the primary transportation mechanism for organic molecules between the molecular cloud and the protostellar nebula, but the complex chemistry of the mantle ices on these grains gets processed by strong shock waves as matter accreted from the parent molecular cloud passes through the accretion shock and is incorporated into the nebular disk. It is not clear what fraction of the organic species have their chemical clocks reset, losing all memory of the parent cloud abundances, and how much is delivered unaltered, ready to undergo further processing in the warmer nebular regions or freeze out again onto the grains for incorporation into planetessimals and comets. Lunine et al. (1991) have calculated that at 30 AU from the center of the solar nebula, water ice amounting to 90% of the grain mass sublimates on entering the disk, whereas the fraction at 100 AU drops to 10%. This material returns to the solid phase in nebular regions beyond 10 AU where the temperature drops to 50 K.

3.2. Centimeter Wavelength Diagnostics

Richards et al. (2003) have pointed out that within the nominal frequency range of the SKA, there have been hundreds of lines detected in interstellar and circumstellar regions, with the highest concentration being around 24 GHz. A total of 31 organic molecules contribute to this detection total, and these species in turn suggest a significant number of as yet undetected lines. At the very least, the increased sensitivity of the SKA and the continuous frequency coverage it provides can determine whether these omissions are just historical observational biases or indicative of the detailed physical environments in the regions.

3.3. HL Tau, A Model For Low Mass Star Formation

There is increasing evidence that low mass star formation involves an analog of the hot cores in regions of massive star formation, therefore we can predict that the same sort of ion-molecule and grain chemistry will be occurring and visible in emission where temperatures are high enough to get the products into the gas phase. In the case of low-mass protostellar nebulae, the question is whether the fractional abundances of these organics (expected to range from 10^{-9} to 10^{-12}) will provide a detectable column density for study when spatially resolved using SKA baselines. The 5 km central portion of the SKA ($\Delta\theta \sim 300$ mas at 22 GHz) can be augmented by some fraction of the baselines in the intermediate array out to 150 km ($\Delta\theta > 10$ mas at 22 GHz) in order to increase the sensitivity and tailor the angular resolution. Continuum observations of the dust in the disk surrounding the T-Tauri star HL Tau made at 1.4 mm with the BIMA array and a 260 mas beam have allowed a very simple model of the disk to be inferred (Welch et al., 2004). The disk has a total mass of > 0.1 $M_\odot$, a semi-major axis of 450 mas (or 63 ± 6 AU), and a position angle on the sky of $135° \pm 5°$. The brightness temperature can be fit with $T_B(r) = 208r^{-3/7}(1 - e^{-\alpha})$, $\alpha = \gamma/r^P$. Where r is measured in AU, the surface density gradient P lies between 0.1 to the SE and 0.4 to the NW, and γ, the optical depth near 1 AU, is ~ 1. The first factor represents the physical temperature of the dust, which has dropped to 50 K at about 27 AU (200 mas), and the second factor tracks the decline in the dust column density with radius. Assuming the A_V extinction value for HL Tau is the same as the value of 2.9 measured for XZ Tau, yields a peak column density for molecular hydrogen of $N_{H2} = 8.2 \times 10^{21}$ molecules/cm^2. The reported fractional glycine abundances in the hot molecular cores range from 2×10^{-9} to 2×10^{-10} with corresponding molecular column depths of $N_{glygine}$ = 2–4 $\times 10^{14}$ molecules/cm^2 and estimated rotational excitation temperatures of 75K to 141K. Assuming the same fractional abundances in the comparable temperature regions of the HL Tau disk yields molecular column densities of $N_{glycine}$ =1.6–16 $\times 10^{12}$ molecules/cm^2, one to two orders of magnitude below the hot cores of the massive star formation regions. The line strengths for the cm transitions in the 10–30 GHz range will in general be weaker than the mm transitions at 100-300 GHz by a factor of $\nu^3 = 1000$. However, the detections were made with a single 12m antenna with main beam efficiency of only 49% at the highest frequency and SIS mixers with $T_{sys} > 200$ K and were bothered by line confusion. The $A_{\rm eff}/T_{\rm sys}$ goal for the SKA between 25 and 35 GHz is 10,000 to 5000 m^2/K whereas the glycine observations were made with a system having $A_{\rm eff}/T_{\rm sys} < 0.5$ m^2/K. Although not a rigorous proof, these estimates suggest that there will be adequate signal strength to permit reasonable spatial differentiation of the organic chemistry in the hot core analogs within low mass star forming regions.

Since the glycine detections are still somewhat controversial, it is possible to scale some other molecular line discoveries to the HL Tau model. Recently, Swift et al. (2004) used the GBT to detect ammonia at 24 GHz in a cold pre-protostellar cloud within L5551 with a line strength of 1.4K. NH_3 is an important player in the complex chemistry of the organic molecules, and many more species can be presumed in the region (indeed C_2S at also detected at 33 GHz). The estimated cloud mass is 2 $M_\odot$. Assuming that the pre-protostellar core collapses to form a star and disk like HL Tau, and scaling to the HL Tau mass, implies the line strength will be a factor of 20 weaker. But the HL Tau disk is hotter and the higher vapor pressure of ammonia should drive the complex organic chemistry and increase the gas-phase abundance for many species. Since the SKA sensitivity will be 100 times better than the GBT, it again appears that detection of organic molecules and some spatial differentiation will be possible in the low mass star forming regions. The same conclusion results from crude scaling of the lines of ammonia, HC_3N and HC_5N detected towards the small TMC1 cloud (Churchwell et al., 1978), and comparing the expected SKA sensitivity with that of the Bonn 100m. Interpreting any spatially differentiated chemistry that is detected will not be straightforward. Schöler et al. (2004) have developed a full radiative transfer model for three components of IRAS 16293-2422, the best candidate for a hot core in a region of low mass star formation. Using extensive mm molecular line searches of this region (Blake et al. 1994; van Dishoeck et al., 1995), it was possible to model three physically and chemically distinct regions, the circumbinary envelope, the circumstellar disks, and an outflow component. The two protostars in this region are separated by about 800 AU, and the radiative transfer model that best fits the data invokes a 'jump' in the gas phase molecular abundances where the envelope temperature reaches 90K and the ice mantles begin to evaporate off the grains. The hot core region is about 150 AU in radius and its molecular constituents probably represent the closest look we have had yet at the raw material for the protoplanetary disk. That's indeed where we, and any other inhabitants of habitable worlds, came from.

4. Summary

Over the first decade of its working lifetime, the SKA will be able to conduct a search for signals from extraterrestrial technologies from several million stars, covering the terrestrial microwave window from 1-10 GHz and setting limits on transmitter powers that represent common transmitters on Earth today. If this search does not succeed, in the next decade of operations, changes will be made in the search strategy and processing equipment that attempt to graft on a survey of the more distant sky. The details of these alterations will depend on he evolution of computational architectures under the influence of external forces.

There appears to be some optimal spatial resolution between that associated with the 5 km central SKA region and that obtained with the intermediate array extending to 150 km at which there will be adequate signal strength for the detection of emission from the complex organic molecules formed in the hot core analogs within regions of low mass star formation. These observations could help to determine how much of the interstellar chemistry is reset versus how much is additionally processed or delivered unaltered into the protostellar accretion disk, and thence into evolving planets.

The SKA is an instrument that could potentially end our cosmic isolation and help us understand how we got here.

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Table 1
Detectability of Terrestrial Analog Signals by the SKA

P_{EIRP} of analogs	$P_T \times G_T$	Range (light-years)	# of stars
Cell phones: 1 W	1 W × 1	.003 [.01]	0
FM radio: 10–100 kW	2–20 kW × 5	0.3 - 1 [1-3]	0
TV: 300 kW	60 kW × 5	2 [6]	0 [4]
1 MW	100 kW × 10	3.3 [10]	$\sim$ 1 (Proxima Cen is 4.3 ly) [11]
Airport Radars: $\sim 10^8$ W	35 kW × 2200	33 [100]	310 [500]
Ionospheric Radars: $2 \times 10^{1}1$ W	150 kW $\times 10^6$	1500 [5000]	$\sim 3 \times 10^7$ [6×10^8]
Arecibo Radar: $2 \times 10^{1}3$ W	1 MW $\times 2 \times 10^7$	15000 [50000]	$\sim 6 \times 10^9$ [$6 \times 10^{1}0$]

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