The Cradle of Life

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The emerging field of bioastronomy is beginning to address one of the oldest questions in science and philosophy: Are we alone? By virtue of its sheer sensitivity, high frequency coverage, and long baselines, the SKA will play a pivotal role in bioastronomical studies. It will be a unique instrument with the capability to image proto-planetary disks in nearby star-forming regions and monitor the evolution of structures within those disks ("movies of planetary formation"). It will also be able to assess the extent to which interstellar molecules are incorporated into proto-planetary disks. It will also be able to reach qualitatively new levels of sensitivity in the search for intelligence elsewhere in the Galaxy, including for the first time the realistic possibility of detecting unintentional emissions or "leakage" (such as from TV transmitters) from nearby stars.

1. Introduction

> Do there exist many worlds, or is there but a single world? This is one of the most noble and exalted questions in the study of Nature.—St. Albertus Magnus, *De Caelo et Mundo*

The existence of life elsewhere in the Universe has been a topic of speculation for millennia among philosphers, theologians, and scientists ("natural philosphers"). In the latter half of the Twentieth Century, a number of discoveries began to ground these speculations with observational data. Among these discoveries are organic molecules in interstellar space and primitive objects such as meteorites; proto-planetary disks and planets themselves orbiting nearby stars; potential sub-surface oceans on multiple icy satellites in the solar system; and "extremophiles," organisms that thrive in environments with extreme heat, acidity, salinity, or other extreme conditions. These various discoveries have given rise to the field of *bioastronomy*, the search for life elsewhere in the Universe.

With its sensitivity and resolution, the Square Kilometer Array (SKA) will make qualitatively new approaches to bioastronomy possible. Two key aspects of bioastronomy that the SKA will enable and that are discussed in more detail in this article are

Terrestrial planet formation Centimeter wavelength radiation can penetrate the dust in protoplanetary disks. With subarcsecond resolution and its high sensitivity, the SKA will be able to observe the inner regions of nearby protoplanetary disks. In these inner regions, the dynamic time scale is of order 1 year so that the SKA will be able to monitor the evolution of nearby protoplanetary disks as terrestrial planets form.

Search for extraterrestrial intelligence (SETI) Detecting transmissions from another civilization would provide immediate and direct evidence of life elsewhere in the Universe. With its sensitivity, not only will the SKA probe deeper into the Galaxy than any previous survey, for the first time it will enable searches for unintentional emissions or "leakage."

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Wilner (this volume) and Tarter (this volume) expand upon these topics, including examples from current instrumentation.

2. Terrestrial Planet Formation

Once a solar-mass star reaches the T-Tauri stage, after approximately 1 Myr, it has dispersed most of its natal circumstellar material. Any residual circumstellar material is present in an accretion/proto-planetary disk. In principle, a proto-planetary disk is readily observed over a wide wavelength range. In practice, there are severe observational challenges including the disk composition, size, and opacity.

Molecular hydrogen at low temperatures is the dominant component of a proto-planetary disk. As such, the disk's major consituent does not radiate at easily accessible wavelengths. Only by observing the thermal emission or scattered starlight from dust grains or trace molecules with abundances of 10^{-4} or less can the disk be studied.

Moreover, a typical proto-planetary disk is small. The nearest star forming regions are the dark clouds in Taurus, Ophiucus, and Chamaeleon at distances of order 150 pc. At these distances, the orbits of Earth and Jupiter are roughly 10 to 100 milliarcseconds in diameter. Thus, high resolution is needed to image these disks. At visible wavelengths, highly accurate point spread function subtraction or coronagraphy is also required in order to remove the glare of the host star.

Finally, although a minor constituent, the dust grains can have column densities of 100 g cm^2 or more. These column densities are sufficient to make the disk optically thick at visible, infrared, and even well into millimeter wavelengths.

Nonetheless, there is great interest in imaging the inner regions of proto-planetary disks. The inner region of a protoplanetary disk is clearly where any terrestrial planets would be forming. Many of the known extrasolar planets are Jovian mass planets within 1 AU of their host star, i.e., much closer than Jupiter is to the Sun. It is not thought that these planets formed *in situ* but that they formed at distances of 5–10 AU from their host star and migrated inward due to gravitational interactions with the proto-planetary disk. More generally, with the continuing discovery of additional extrasolar planets, planetary systems are being recognized to have a large diversity. The study of the inner regions of proto-planetary disks may very well reveal as-yet unknown types of planetary systems.

The SKA will make significant contributions to three aspects of planetary formation.

2.1. Dust Grain Growth

The heuristic picture of planetary assembly is that it begins in a disk composed of dust and gas. The initial dust grain size is probably submicron, comparable to that for interstellar dust particles. Within the proto-planetary disk, the dust grains begin to "stick" together. As they do so, they decouple from the disk gas and begin to interact gravitationally. The dust grains continue to accrete, forming "pebbles," then "boulders," and finally planetismals.

One difficulty with this scenario is that, given their kinetic energies, how dust grains interact so as to "stick" together rather than destroy each other is not clear. The crucial size regime is of order 1 mm to a few centimeters. Smaller size dust grains are not likely to destroy each other in their interactions, and meter-sized "boulders" can begin to accrete gravitationally. However, that dust grains are able to stick together and form millimeter- and centimeter-sized particles is clear from the existence of the Earth as well as from the spectral energy distribution for stars like TW Hya [2,5].

In order to probe this crucial particle size regime, the observational wavelength must be within a factor of few of the particle size or roughly from hundreds of microns to a few centimeters. These wavelengths are well matched to the wavelength range for the SKA. Its current specifications call for observations to wavelengths as short as 1.2 cm (25 GHz), and it may be possible to extend its wavelength coverage to 0.85 cm (35 GHz). The SKA will allow for the first time multi-wavelength imaging that will localize regions within the disk with different spectral signatures and therefore different grain properties.

2.2. Gaps in the Proto-planetary Disk

A key prediction of planetary formation models is that protoplanets should interact with the proto-planetary disk, opening gaps in it. Through gravitational interactions, material exterior to the protoplanet gains angular momentum and moves to larger radii while material interior to the protoplanet loses angular momentum and moves to smaller radii. Indeed, a number of T Tauri stars, such as TW Hya, show spectral signatures (mid-infrared deficits) that are interpreted as resulting from the formation of gaps in their disks.

Figure 1 shows the result of a representative simulation in which a protoplanet has produced a gap in a proto-planetary disk. The protoplanet has excited spiral density waves near its inner and outer Lindblad resonances. Shock wave dissipate angular momentum, and the disk material moves away from the protoplanet's orbit. For a Jupiter-mass planet at 5 AU from its host star, the gap width is roughly 1 AU. Planets as low as 0.1 Jupiter masses appear to open significant gaps, and even lower mass planets can still excite density waves and produce potentially detectable structures. Much more sophisticated simulations are being undertaken, incorporating magnetohydrodynamics and fully three-dimensional hydrodynamics. Ultimately, however, these simulations should be grounded with observational constraints.

With baselines of order 1500 km, the SKA will have sufficient angular resolution to *image directly* nearby proto-planetary disks and detect gaps, rather than relying on model-dependent interpretation of spectra. In this sense, the SKA will provide a unique probe of proto-planetary disks. For comparison, the Atacama Large Millimeter Array (ALMA) will also be able to detect proto-planetary disks, but it will not have sufficient resolution to resolve their sub-AU–scale structures.

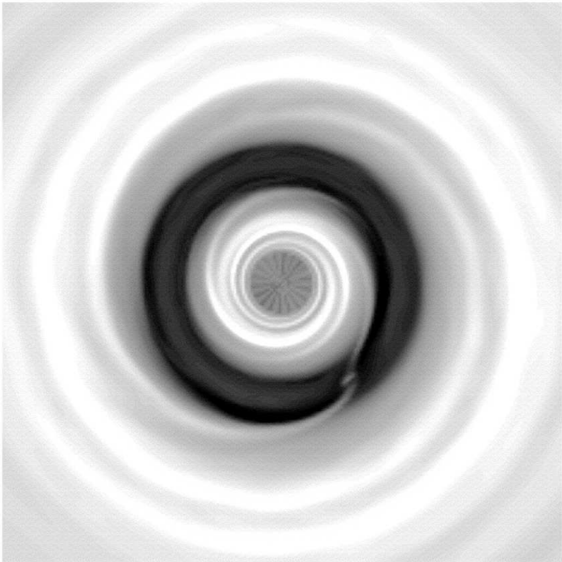

Figure 1. A representative numerical simulation of a Jupiter-mass planet forming within a proto-planetary disk (from [1]). White indicates high density while black indicates low density. The planet itself is within the gap (dark annulus), in a small accretion stream. While the planet itself is extremely difficult to detect at any wavelength, the wide gap is a strong marker of its presence. The SKA will have the resolution to resolve proto-planetary disks such as this one, detect the formation of planets, and even monitor the evolution of the disk.

2.3. Mind the Gaps

Even more impressive than merely taking "snapshots" of proto-planetary disks is that the SKA will be able to form *movies* via synoptic studies. The dynamical time scale for material orbiting a 1 $M_\odot$ star at 1 AU is 1 year. By making observations spaced roughly a month or so apart, the SKA will follow the proper motions of mass concentrations and structures within a disk. In essence the SKA will allow planetary formation to be followed in near real time.

3. The Search for Extraterrestrial Intelligence (SETI)

We currently have no reason to believe that life on the Earth is unique. While we know of no extrasolar planets comparable to Earth, we do know of at least two terrestrial mass planets orbiting the pulsar PSR B1257+12 and we know of more planets outside of the solar system than inside. Current limitations to finding terrestrial-mass planets around main-sequence stars are "merely" technological. However, planets with a few to several tens of Earth masses have been found around nearby main-sequence stars, and it is expected that space-based missions (e.g., Kepler, Darwin, Gaia, and Terrestrial Planet Finder) will discover and begin to determine the frequency of terrestrial-mass planets around main-sequence stars.

Unfortunately, there are severe constraints on the detection of life by remote sensing means on any extrasolar terrestrial-mass planets discovered in the next few decades. At best, the planned space missions will be able to obtain a spectrum of the atmosphere of any terrestrial mass planet. Various compounds such as ozone (O_3) and methane (CH_4) are being considered as potential biomarkers for surface life because these compounds are not thought to be produced in any large quantities by abiological processes and they should be removed rapidly from a planet's atmosphere unless replenished on a constant basis. Nonetheless, there is the potential for "false alarms," resulting from currently-unrecognized abiological processes that could give rise to substantial levels of O_3, CH_4, or other potential biomarkers.

An alternate approach is to search for evidence of alien technology [8]. By virtue of the fact that radio emissions from the Earth make it detectable over interstellar distances, a natural strategy is to search for "artificial" radio signals. Such signals would be ones thought impossible to be produced in a celestial source such as those having a time-bandwidth product $\Delta\nu\Delta t \approx 1$. This search strategy has the benefit that, with an instrument with the sensitivity of the SKA, a substantial fraction of the Galaxy can be probed, in comparison to the relatively limited region for detection and spectroscopy of terrestrial-mass planets ($\approx$ 10 pc for the forseeable future).

In searching for evidence of technological civilizations, radio wavelengths offer a number of advantages. First, a wide range of radio wavelengths can propagate across the entire Galaxy suffering essentially no absorption. This range conservatively covers some 4 orders of magnitude. At frequencies below roughly 100 MHz (3-m wavelength) free-free absorption becomes increasingly important. At frequencies above roughly 1 THz (300-micron wavelength), dust absorption becomes increasingly important. Within this range, though, there is very little absorption as evidenced, for instance, by radio observations of the Galactic center which is obscured by approximately 30 magnitudes of absorption at visible wavelengths.

Second, there is a natural minimum in noise sources in the range of 1 to 10 GHz. Below approximately 1 GHz the Galactic synchrotron background resulting from relativistic electrons in the Galaxy's magnetic field increase the system temperature and thereby decrease the sensitivity of any radio telescope. Above approximately 10 GHz the cosmic microwave background contributes to a reduced sensitivity as does increasing quantum noise within detectors. This frequency range also contains atomic lines from biologically-important atoms and compounds. The most famous of these is the "waterhole," between the 1.42 GHz hyperfine transition of neutral hydrogen and the series of lines around 1.65 GHz due to the OH radial.

Third, radio photons are relatively easy to produce, and radio transmitters capable of being detected over interstellar distances should be able to be constructed by even "nascent" technological civilizations. For instance, terrestrial broadcast FM and TV transmitters, with powers of order 10–100 kW, routinely outshine the Sun by factors of 106 or more [8], and the scientific radar on the Arecibo Observatory could be detected by a comparable-sized telescope on the other side of the Galaxy.

Tarter [8] has summarized the SETI programs published to date (approximately 100), the majority of which have been at radio wavelengths. The sensitivities of all of the radio SETI programs to date has been such that, in order to be detected, any transmitting civilization would have to be fairly altruistic and transmitting a powerful beacon in order to be detected. For instance, transmitting power levels are described commonly in terms of Kardashev [3] types. The weakest of these is a Type I civilization that devotes a substantial fraction of the terrestrial energy consumption (4×10^{12} W) to interstellar communication. While some terrestrial transmissions are detectable over interstellar distances, our civilization transmits no beacons for the purpose of being detected, thereby devoting essentially 0% of its energy consumption to interstellar communication. For power levels more typical of terrestrial transmitters, particularly those that would be detected via their unintentional emissions, current radio SETI programs could not detect them at distances of even 1 pc. Of course, given that there are no stars within 1 pc of the Sun, this is not a particularly stringent limit.

A SETI program conducted with the SKA offers a number of potential improvements over existing and near-future SETI programs. The first, and most important, is the sheer sensitivity of the SKA.

Table 1 illustrates the range of potential signals detectable by the SKA, assuming a detection threshold for narrowband signals of 10^{-28} W m^{-2} and with signal processing comparable to what has been done to date. This detection threshold already represents a *two orders of magnitude* improvement over current searches. This sensitivity limit is consistent with a few minutes of observation per target, with millions of target stars, over a few years of telescope time, and could detect signals consistent with terrestrial airport radars around a few hundred of the nearest stars. By comparison, existing searches have targetted no more than about 1000 stars.

The second improvement offered by the SKA will be in processing capability. The above targeted search of stars assumes that a nominal number of multiple phased-array beams will be used to increase the efficiency of the search, but that otherwise the search will be similar to what has been conducted to date. Straightforward extrapolations of computational capabilities suggest that these assumptions about signal processing are overly pessimistic, as they assume no signal processing gain beyond what is now possible and no new algorithm development. A decade 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 both to increase the number of phased-array beams (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. 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 at this sensitivity level could explore most of the likely habitable stars out to about 300 pc for a range of transmitter powers that are prevalent in our own 21$^{\rm st}$ century technolgy, including potentially reaching power levels *comparable to terrestrial TV transmitters* for the nearest stars.

Table 1
Detectability of Terrestrial Analog Signals by the SKA

Signal	Power (W)	Range (pc)	Number of Stars
Detection Threshold = 10^{-28} W m^{-2}			
TV	3 × 105	2	0
1 MW signals	106	1	1
Airport Radars	108	33	310
Ionospheric Radars	2×10^{11}	500	3 × 107
Arecibo Radar	2×10^{13}	5000	6 × 109
Detection Threshold = 10^{-29} W m^{-2}			
TV	3 × 105	6	4
1 MW signals	106	3	11
Airport Radars	108	100	500
Ionospheric Radars	2×10^{11}	1500	6 × 108
Arecibo Radar	2×10^{13}	15,000	6×10^{10}

Power levels are in terms of the equivalent effective isotropically radiated power (EIRP).

4. Other SKA Contributions

To what extent is the origin of life connected to interstellar chemistry? Stars, and their planets, form in molecular clouds, the chemistry of which is overwhelmingly organic. It is only poorly understood, though, to what extent, if any, the molecules formed in molecular clouds could be delivered to a terrestrial planet and help form the inventory of prebiotic chemical building blocks available to participate in the origin of life. In this respect, the slight excess measured for the L-enantiomer over the D-form in abiotic amino acids within the Muchison and Murray meteorites [6] and the recent claim for the detection of glycine in hot cores of high mass star formation regions [4] are particularly suggestive.

A key uncertainty with the notion of interstellar chemistry serving as the basis for life is the delivery mechanism. Dust grains would appear to provide the primary transportation mechanism for organic molecules between the molecular cloud and the protostellar nebula, but the complex chemistry of their mantle ices should be processed by strong shock waves as matter is accreted from the parent molecular cloud and incorporated into the nebular disk. It is possible that these shocks destroy much of the complex chemistry built up within the molecular cloud.

Many of the studies of star forming regions have been carried out at IR, sub-millimeter, and millimeters wavelengths. Richards, McCombie, & Zijlstra [7] 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. The increased sensitivity of the SKA and the continuous frequency coverage it provides will allow this possible connection to be probed, by assessing the extent to which interstellar molecules can be detected in low-mass star forming regions, potentially even within proto-planetary disks themselves.

5. Summary

The SKA will play a pivotal role in bioastronomical studies due to several aspects of its design not found in current radio telescopes (nor any telescopes in other wavebands). Table 2 summarizes the key SKA specifications relevant to the SKA's bioastronomical studies.

Table 2
SKA Specifications and Bioastronomy

Item	Requirement	Motivation
Sensitivity	$A_{\rm eff}/T_{\rm sys} \geq 104$ m^2 K^{-1}	imaging proto-planetary disks
		detecting "leakage" from other civilizations
		molecular chemistry
Frequency Coverage	1–25 GHz	1–10 GHz for SETI
		25 GHz for proto-planetary disk studies
		$>$ 10 GHz for molecular chemistry
	25–35 GHz (goal) (reduced sensitivity)	molecular chemistry, proto-planetary disk studies
Configuration	$>$ 1500 km baselines	imaging proto-planetary disks
Configuration	"core" $\approx$ 5 km	high brightness temperature sensitivity for molecular studies
Signal Processing	$\gtrsim$100 phased-array beams	targeted SETI programs

The SKA will be a unique instrument with the capability not only to image proto-planetary disks in nearby star-forming regions but to monitor the proper motions of structures within those disks. We anticipate movies that the SKA will generate movies showing a (small) fraction of the formation process of a terrestrial planet. It will also probe the extent to which interstellar molecules are delivered to proto-planetary disks.

The SKA will reach qualitatively new levels of sensitivity in the search for intelligence elsewhere in the Galaxy. For the first time, unintentional emissions or "leakage," at levels comparable to those of terrestrial transmitters potentially even TV transmitters, will be detectable.

Combined with other bioastronomical facilities, on the ground, in space, and on other planets in the solar system, the SKA will play a key role in finding life elsewhere in the Universe.

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