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The Cradle of Life and the SKA

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We provide an overview of the exciting capabilities of the SKA in the Cradle of Life theme. With the deployment of the high frequency band 5 receivers, the phase 1 of the SKA can conduct headline science in the study of the earliest stages of grain growth in proto-planetary disks. SKA1-MID can map the 2 cm continuum emission at a resolution of 4 au in the nearest systems and therefore begin to probe the distribuion of cm-sized particles across the snow line. This frequency range will also enable deep searches for pre-biotic molecules such as amino acids from pre-stellar cores to the cold, outer regions of proto-planetary disks where cometary material forms. The lowest frequency capabilities of SKA1 can be used to examine the magnetic fields of exo-planets via their auroral radio emission. This gives unique insight into their interiors and could potentially detect exo-moons. Across the full frequency range, the SKA1 will also carry out systematic, volume-limited searches of exo-planet systems for signals from technologically advanced civilizations. The sensitivity of SKA1 means that these only need to be at the level of typical airport radar signals in the nearest systems. Hence, the SKA1 can conduct high impact science from the first steps on the road to planets and life, through areas affecting the habitability of planets, and ultimately, to whether we are alone in the Galaxy. These inspirational themes will greatly help in the effort to bring SKA1 science to a wide audience and to ensure the progression to the full SKA.

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1. Introduction

The origin of life is as great a question as the origin of the universe. In terms of the interests of the general public it is probably second to none. A suitably equipped SKA will yield new and unique insights into the different stages of the origin and existence of life elsewhere in the Galaxy.

First, the combination of sensitivity and resolution of SKA1-MID equipped with band 5 receivers will probe the first steps on the road to forming habitable planets. Only cm-wave instruments can directly track the growth of dust grains through the important cm-sized regime. For the nearest proto-planetary disk systems SKA1-MID can start to study grain growth processes inside the snow line, which is the realm of rocky planet formation.

Secondly, SKA1-MID can detect the presence of molecules that are of biological interest such as amino acids. These heavy molecules that are the very building blocks of life have detectable transitions in the band 5 frequency range. The sensitivity and resolution of the core of SKA1-MID will enable searches for these pre-biotic molecules in the outer regions of proto-planetary disks free from the line crowding and strong dust emission at millimetre wavebands. It is in these cold outer disk regions where their incorporation into comets could allow the possibility of delivery on to rocky inner region planets.

The next stage of the origins story is the characterization of the planets themselves. A unique contribution of radio observations is the study of planetary magnetic fields via auroral emission. Not only do magnetic fields give clues to the nature of planetary interiors, but they also play a role in protecting planetary surfaces from the high energy stellar wind particles that give rise to the aurorae in the first place. SKA1-LOW has the potential to study the magnetic fields of Jupiter-like planets at moderate distances from their host stars. Modulations of these radio emissions will expand the field of comparative magnetspheric physics to a much broader range of star-planet interactions than in our solar system. They may also indicate the presence of potentially habitable exo-moons.

Last, but by no means least, is the potential for the SKA to detect directly the existence of intelligent life via technologically produced radio signals. Such a discovery would of course be momentous in the history of humankind. However, the sensitivity of the SKA1 is such that interesting conclusions can be drawn from upper limits on targetted samples of the ever growing numbers of known exo-planet systems. The ability to detect typical levels of leakage radiation produced by technological civilizations like ourselves takes the search for extra-terrestrial intelligence to a whole new level. Commensal observing modes with the SKA will enable searches of much larger areas of parameter space for such signals than has ever been possible before.

2. Grain Growth in Proto-Planetary Disks

The unique value of the SKA in this context is that the only unambiguous way of detecting the presence of cm-sized particles is to measure the strength and the spectral index of the continuum emission at cm wavelengths as shown in Figure 1. In principle, the longer the wavelength we can use the better, to probe ever larger grains, but of course the flux is falling off at least as fast as λ^{-2} and so there is a big trade off with sensitivity. Several studies have shown evidence for a flattening in the spectral index of the overall SED showing that grain growth is taking place somewhere in the proto-planetary disk (e.g. Ricci et al. 2010).

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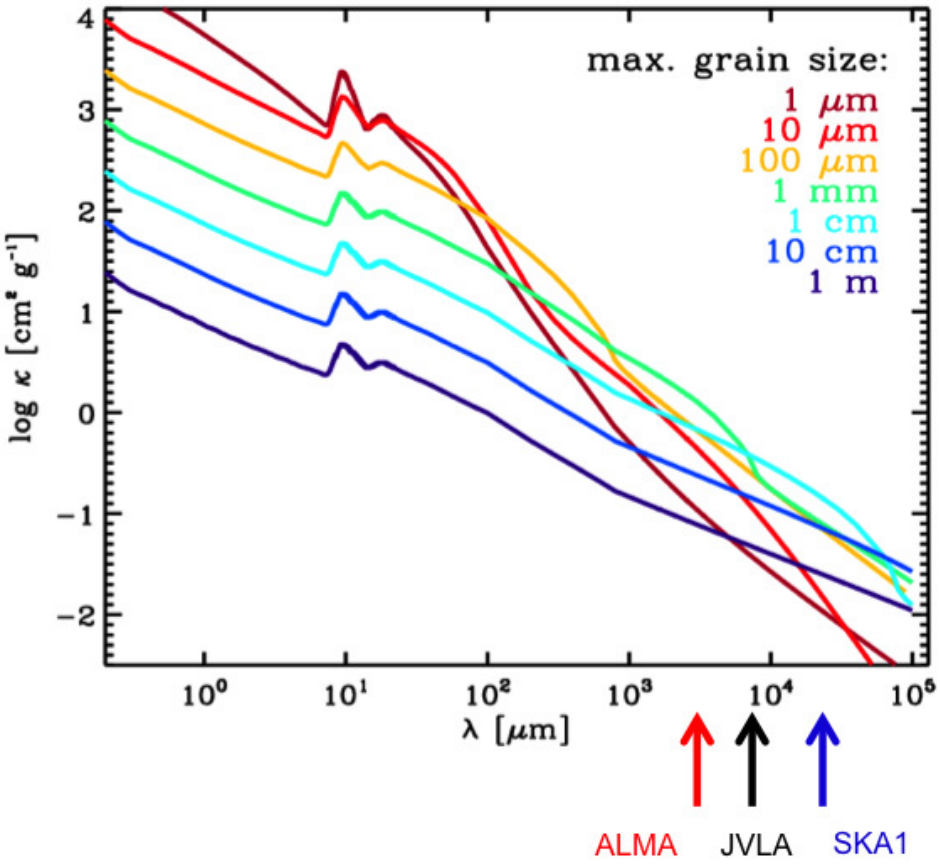


Figure 1: Opacity curves for grains of different sizes showing the flattening of the slope at cm wavelengths as the grains become cm-sized. The wavelengths at which ALMA, JVLA and SKA1-MID can deliver matching-beam data with a resolution of 40 mas are indicated. This corresponds to the ∼4 au radius of the snow line in the nearest proto-planetary disks.

The challenge now is to find out where and how grain growth proceeds as this is the first crucial step on the road to planet formation. As discussed in Testi et al. (2015; these proceedings) there are considerable challenges involved in grains growing through the cm size regime and that growth may only occur in particular locations within disks where dust becomes trapped. Investigating these phenomena requires high spatial resolution at cm wavelengths (e.g. Pérez et al. 2012).

Another key related question is which mechanisms lead to the formation of the very different terrestrial and Jovian planets. This will require studies of grain growth either side of the snow line for water ice, which is located at a radius of a few au from the star. As discussed by Kretke & Lin (2007) the interplay of the additional opacity at the snow line with the formation of dead zones in the turbulence due to the magneto-rotational instability can overcome the barriers to grain growth. For typical proto-planetary disks around solar-type stars the snow line is expected to be at a radius somewhere in the range of 1 to 10 au depending on the accretion rate. The snow line in the well-studied TW Hya disk is deduced from observations to be at a radius of around 4 au (Zhang et al. 2013). Therefore at the typical 100 pc distances of the nearest proto-planetary disks this requires

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a spatial resolution of about 40 mas to resolve the snow line. This is precisely the resolution of SKA1-MID operating at the top end of the band 5 frequency range.

The size of the large grains in a proto-planetary disk are deduced from the shape of the spectral energy distribution at each location in the disk. This is best done across a broad spectral range all the way from mm through to cm wavelengths. At the resolution needed to resolve the snowline this can be achieved with SKA1-MID operating at 2.5 cm in combination with the JVLA at 7 mm and ALMA at 3 mm as is illustrated in Figure 1.

To demonstrate the feasibility of such an experiment we show a simulated 11.3 GHz continuum observation of a typical proto-planetary disk model in Figure 2. The model is based on that presented by Isella et al. (2009) for a disk with a symmetric distribution of $0.01 M_{\odot}$ of material as in the minimum mass solar nebula surrounding a $1 M_{\odot}$ star. The disk has a radius of 120 au and is viewed at an angle of 45° at a distance of 125 pc. Dust in the disk has an emissivity law slope of $\beta = 0.5$ and has a total flux of 180 μJy. Here it is imaged at the full resolution of SKA1-MID where the unifrom weighted beam has a size of 35×40 mas. This simulation was for a 1000 hour deep field integration and clearly maps out the dust emission at this high resolution. The peak intensity is 4 μJy/beam, equivalent to a brightness temperature of 30 K, and the noise level is 0.07μJy/beam (0.5 K). Hence, SKA1-MID can clearly make a high impact in the mapping out of grain growth in proto-planetary disks at high resolution in targeted regions.

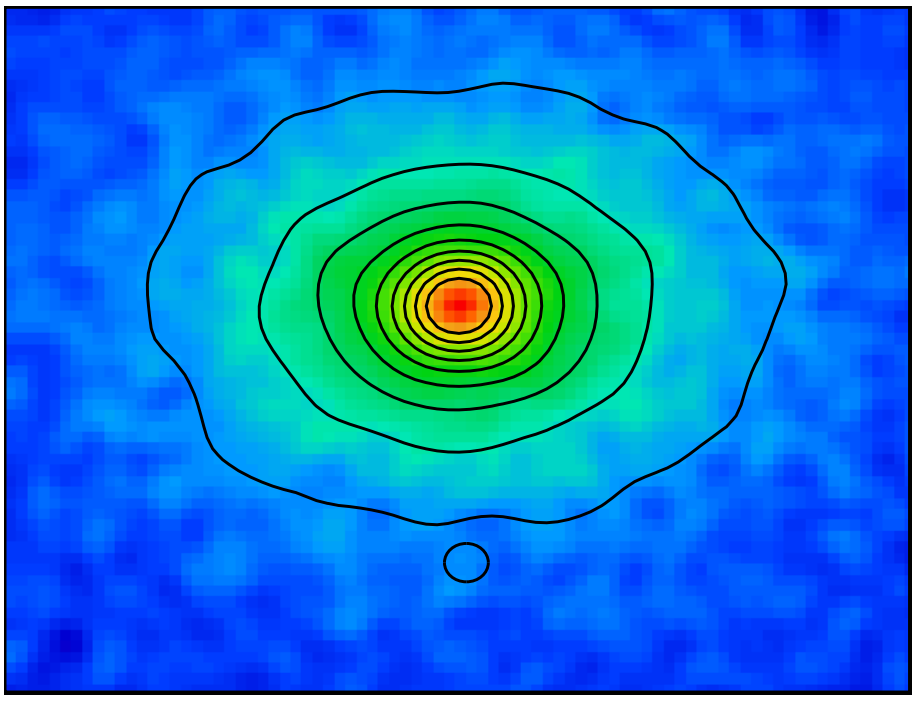


Figure 2: Simulated continuum image of a proto-planetary disk using a 2 × 2.5 GHz bandwidth from 8.8 to 13.8 GHz. Contours run from 5, 10, 15, ...,45 times the 0.07μJy/beam noise level. The image is about 0.85 × 0.65 arcseconds in size and the 35 × 40 mas beam is indicated. See text for details. Note that real disks are likely to have significant structure in them as in Figure 1 of Testi et al. (2015).

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3. Pre-Biotic Molecules

As discussed by Testi et al. and Codella et al. in these proceedings another potential high impact area for SKA1-MID operating at band 5 is the detection of pre-biotic molecules in both proto-planetary disks, outflows and pre-stellar cores. The high sensitivity over a large range of angular scales of the SKA1-MID configuration is well suited to the search for these building blocks of life. The concentrated 1 km core results in a good brightness temperature sensitivity on the several arcsecond scales necessary to detect molecules in the pre-stellar core sources. For the cold, outer regions of proto-planetary disks then a resolution of around an arcsecond is well-matched to the 100 au spatial scale. In this way SKA1-MID can attempt to track the origin and evolution of pre-biotic molecules and trace their journey from the interstellar medium into the regions where they could be incorporated into cometary material at the outer edges of young planet forming systems (e.g. Ceccarelli et al. 2014).

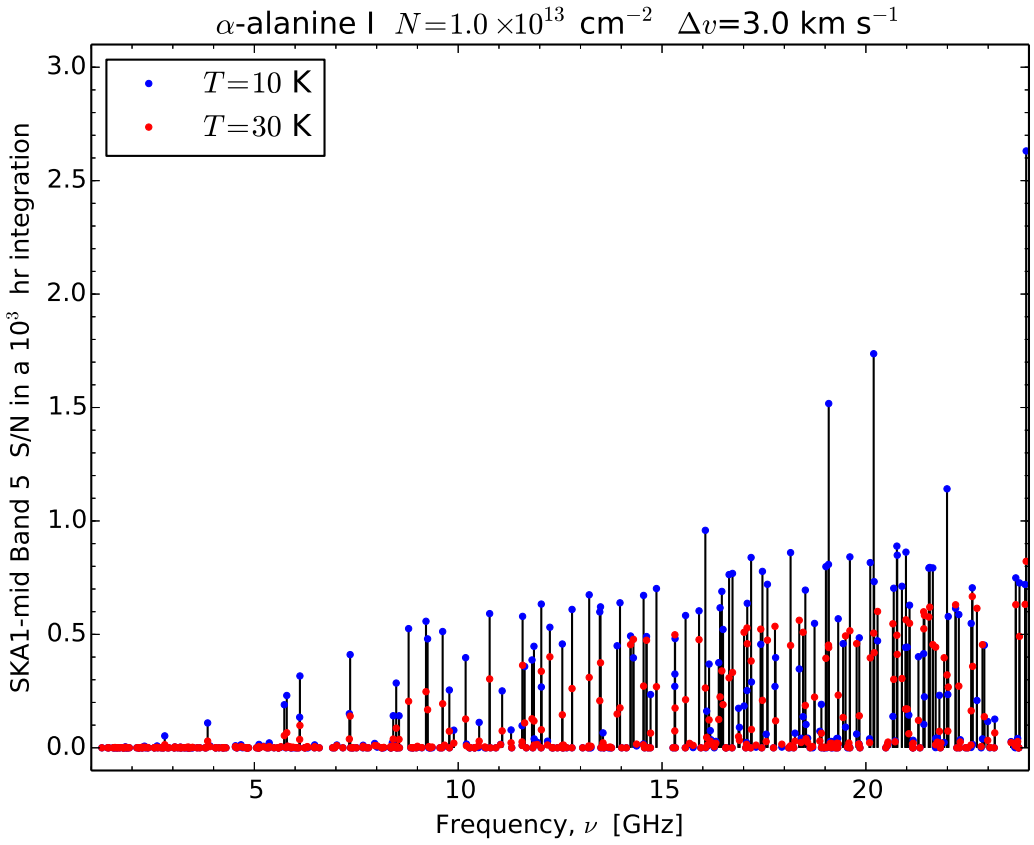


Figure 3: Simulated signal-to-noise ratio that would be achieved with a deep, 1000 hour integration with a 190 dish SKA1-MID for the emission from the spectral lines of the conformer I of α-alanine in LTE for two different temperatures. The frequency range covered includes the baseline design band 5 range from 4.6 to 13.8 GHz as well as the possible extension up to around 24 GHz being considered in the SKA's Advanced Instrumentation Programme. Note that the assumptions here indicate that these lines are not quite detectable, but see text for additional considerations.

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Testi et al. and Codella et al. demonstrated that detections of the simplest amino acid glycine are possible with SKA1-MID in band 5. In Figure 3 we show the expected LTE strength of lines from the next most complicated amino acid, alanine. The column density assumed here would correspond to an abundance of alanine of about 10^{-12} relative to hydrogen in a proto-planetary disk like that in TW Hya where the gas surface density is about 15 g cm^{-2} or the hydrogen column density is 6×10^{24} cm^{-2} (Andrews et al. 2012). This is compared to the abundance of 10^{-11} that Testi et al. assumed for glycine. Figure 3 indicates that if alanine is similarly abundant then it would be detectable by SKA1-MID if it was emitting in LTE in the cold mid-plane of the outer regions of a proto-planetary disk. However, as shown by Faure et al. (2014), these cm-wave transitions from such molecules may well undergo boosting by NLTE effects, i.e. they might be weakly masing. Although this would make their interpretation difficult as stated by Testi et al., it would help the detection and identification of these important pre-biotic molecules.

4. A Young Cluster Deep Field

It is clear from Testi et al. and Codella et al. that both the high resolution grain growth study and the search for amino acids will require very deep integrations of order 1000 hours with SKA1-MID. Fortunately, the study of grain growth and pre-biotic molecules in proto-planetary disks could be done simultaneously. The rebaselined design specifies 64 000 channels per IF, which means that the full 2 x 2.5 GHz bandwidth can be observed with a channel spacing of around 1 kms^{-1} in the 8.8 to 13.8 GHz range. This matches the line width in outer disk regions (Qi et al. 2004) and is therefore adequate for line detection experiments, although detailed confirmation and kinematics would require higher spectral resolution follow-ups. A reasonable spectral resolution is also required for the continuum spectral index measurement since it is important to ensure that low level line contamination is corrected for.

The fact that most young stars and their proto-planetary disks form in clusters also gives a significant multiplex advantage due to the large field of view of the SKA dishes. In typical young clusters about 10 targets will be available in the 6 arcminute field of view at the high frequency end of band 5 (e.g. Gutermuth et al. 2009). One rich region would be the centre of the ρ Oph A cluster (Figure 4). This pointing would contain 7 class I sources and 10 class II young stellar objects (Gutermuth et al. 2009) so that different evolutionary stages can be studied at the same time as well as a range of stellar masses.

A deep field experiment on a single pointing at the centre of a rich young cluster would also enable other important science goals to be achieved with the same dataset. The younger sources invariably drive ionized jets as discussed by Anglada et al. (these proceedings). A deep, high resolution image will easily provide a very detailed view of the free-free continuum and the radio recombination line emission from the jets. A high resolution spectral index and/or recombination line map will allow the separation of the ionized gas emission from the dust emission in the disk and is another important pre-requisite to the study of grain growth in the innermost regions.

To build up such a deep field will of course require many repeat visits to the target region. The cadence of such observations could then enable the time monitoring of the ionized gas emission from the young cluster sources. For the thermal jets this will allow the study of variability in jet morphology and proper motion measurements to characterise the mass-loss rate and test driving

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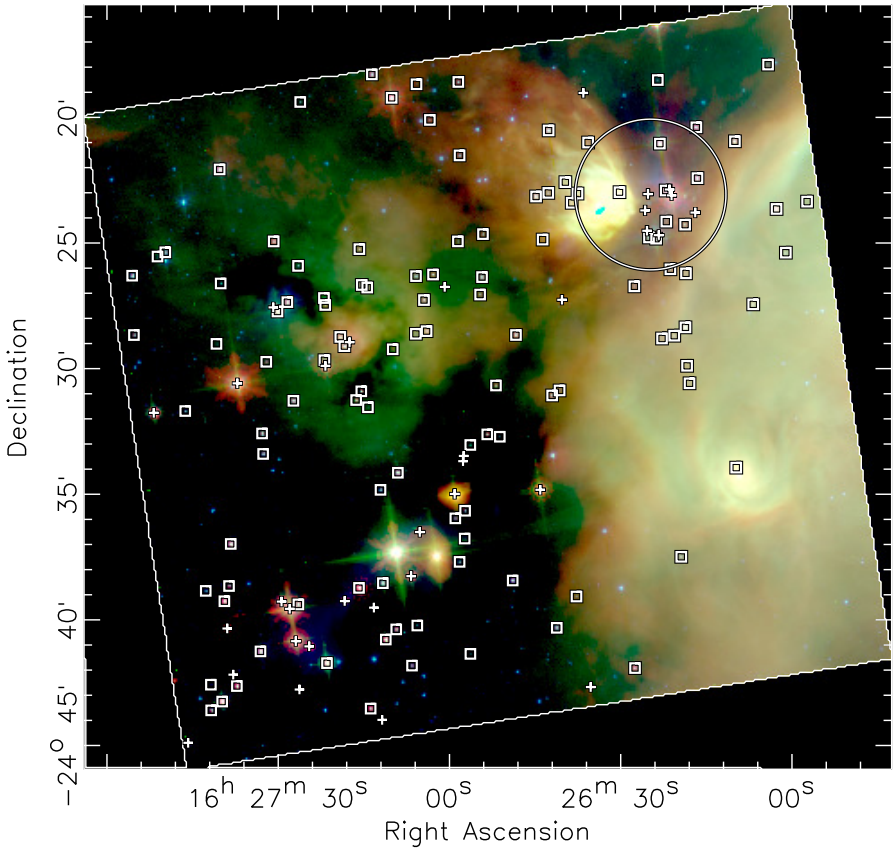


Figure 4: Spitzer three-colour image (3.6μm (blue), 8.0μm (green), 24μm (red)) of the L1688 region of ρ Oph star forming region. Class I and II young stellar objects are indicated by the plusses and squares respectively. Note the clustering of young sources that enables many sources to be studied in one deep pointing with SKA1-MID. One 6 arcminute field of view centred on the ρ Oph A cluster is indicated at the top right.

mechanism models. Variability may also help identify regions of the disk that are contaminated by jet emission as, in general, this is expected to vary on more rapid timescales than the dust emission from the disk. Furthermore, the long duration monitoring will provide a wealth of data with which to study the magnetic flaring activity in the innermost regions where the protoplanetary disk is expected to be disrupted by the magnetic field (e.g. Liu et al. 2014). These highly energetic events have been proposed as being responsible for the chondrules found in meteorites (Shu et al. 2001) and so may help complete the picture of the make-up of planet forming material.

Finally, if some of these observations over the period of a year or so are combined with VLBI runs then the 3D tomography of non-thermal sources in the targeted young cluster can be completed simultaneously as well. As discussed by Loinard et al. (these proceedings) knowledge of the 3D structure and kinematics, via proper motions and radial velocity, will provide stringent tests of cluster formation models. The VLBI resolution will also be able to locate accurately where in the proto-planetary disk the non-thermal emission originates. This will further help elucidate its role

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in the thermal and chemical processing of the solid material in the planet formation zone. Overall, such a young cluster deep field experiment could yield a wealth of information on star and planet formation processes and the origins of pre-biotic molecules.

5. Planetary Magnetic Fields and Habitability

Another key question in the Cradle of Life theme is the habitability of planets once they are formed. Many aspects make up this question of course, although the starting point is the presence of liquid water, and usually this means a planet in the habitable zone. Other important aspects of habitability can be probed uniquely by the magnetic properties of the planet. As described in detail by Zarka et al. (2015; these proceedings) the existence and properties of a planet's magnetic field can be diagnosed using the lowest frequencies of the SKA.

A planet only has a magnetic field if dynamo action can generate such a field through the combination of differential rotation and convection in a conducting fluid in the planet's interior. For rocky terrestrial planets this means a liquid iron core. This in turn has implications for geological activity on the planet and the recycling of volatile gases via volcanic outgassing affecting the planet's atmospheric composition. For icy moons such as Jupiter's Ganymede, the conducting medium is thought to be a mineral rich, sub-surface ocean. Given the increasing evidence for extremophiles found in sub-glacial Antartic lakes (Christner et al. 2014), such icy exo-moons could in principle harbour biological activity beneath their surfaces. These exo-moons do not need to be in the traditional habitable zone as the extra heat required to melt the water ice is provided by the tidal heating by its large planetary host.

The probing of planetary magnetic fields via radio studies also impinges on other aspects of habitability. Such fields protect both the planet's atmosphere and surface from high energy particles coming in from either cosmic rays or the host star's solar wind. Such a wind can play a role in eroding a planet's atmosphere over time as well as other effects on atmospheric composition (Brain et al. 2013). Modulation of the auroral radio signals will enable determination of the planets rotation period, which is important in setting day/night temperature differences. Measurements of the inclination of the planet's rotation axis to its orbital plane will reveal whether the planet experiences seasonal changes. Such aspects may well be important in the emergence of life on Earth-like planets.

The SKA is unlikely to be able to detect magnetic fields on terrestrial planets if they are of similar strength to the Earth's since they will emit at too low a frequency. Much more likely are detections of Jovian planets. Here there is considerable interest in the potential to detect exo-moons that are difficult to detect in any other way. Jovian moons leave an imprint on the pattern of auroral emission, which is then revealed as periodic modulation of the radio emission. This can be the case whether the exo-moon itself has a magnetic field (e.g. Ganymede) or not (e.g. Io). If the exo-moons are icy and magnetic then they also hold out the prospect of hosting biological activity. On the timescale of SKA2 we will be learning much more about these prospects via ESA's JUICE mission (Grasset et al. 2013).

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6. Search for Extra-terrestrial Intelligence

Of course, the greatest question of them all perhaps is not just whether life can exist on other planetary systems, but whether it can evolve into intelligent life that is technologically advanced. As described by Siemion et al. (2015 these proceedings), searches in the radio waveband for such extra-terrestrial intelligence (SETI) has a long tradition, much of it privately funded. Since the beginnings of the SKA project SETI has formed part of the core science case (Tarter et al. 2004). In the mean time the reasons why SETI is now 'mainstream' have become even stronger. The Kepler mission has now shown that basically every star has a planetary system (Dressing & Charbonneau 2013). Furthermore, a number of Earth-like planets in the habitable zone are known and this number will only increase (e.g. Quintana et al. 2014). So the uncertainty over the widespread availability of planetary hosts has been removed.

The other aspect of the SKA that means SETI searches should be central to its science programme is its sheer sensitivity. The fact that the SKA can detect the typical types of radio signals we on Earth emit as we go about our 'everyday business' means that well-defined questions can be addressed. also opens the possibility of detecting deliberate transmissions from sources of lower power (or at greater distances) than ever before. The large frequency coverage and flexibility of the SKA also make it the ultimate SETI machine.

As detailed by Siemion et al. a complete volume-limited search of the nearest one thousand stars (and hence, their planetary systems) within about 15 pc down to the levels of typical airport radar signals is easily possible in 1000 hours of observing with SKA1. Of course, these targets are exactly the same as those to be searched for auroral emissions from planetary magnetic fields as described above. So on SKA1-LOW these targetted searches can be done in parallel. On SKA1-MID the SETI observations can very naturally be carried out in combination with a wide variety of other large area surveys, using one beam to target a nearby star in the field of view, whilst a few other beams are used to exclude terrestrial origins for any signal detected. As with the transient and pulsar cases, the more commensality that can be achieved with SKA observations the more science can be delivered. With the kind of sensitive, volume-limited search outlined above we can start to make significant progress into evaluating the probability of intelligent life evolving on other planets in the Galaxy.

7. Summary

Overall the rebaselined SKA1 will enable a wide range of exciting discoveries under the Cradle of Life heading. SKA1-MID with its high frequency capability will examine the tricky first steps of building terrestrial planets up from small grains through to rocks. In addition, it will conduct sensitive searches for the large molecules that are the very building blocks of life in the cold, dark places where stars and planets form. At the other end of the SKA1 frequency range, SKA1-LOW will study the magnetic fields of the exo-planets themselves, providing insights into the habitability of these worlds. At the same time the full range of SKA1 frequencies will be systematically searched for any signs of intelligent life on the nearby exo-planets and beyond. Each of these areas is of great interest to the general public. These topics are simple to convey and are especially good for getting young people interested in the science enabled by the SKA. Hence, we expect the Cradle

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of Life area to play a major role in the wider impact of the SKA on the general public. This in turn will greatly assist in garnering the funding required for both Phase 1 and beyond.

Acknowledgments

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