Life Cycle of Stars SWG Summary

Sean M. Dougherty
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`sean.dougherty@nrc.ca`

Participants:

Sean Dougherty (NRC, Chair), Dave Wilner (CfA), Corrado Trigilio (IRA-CNR), Elana Franciosini (Palermo), Miguel Perez-Torres (IRA-CNR)

1 Remarks

The promise of a large collecting area as proposed for the SKA presents for the first time a significant capability for high fidelity observations of thermal processes. This capability is reflected in Level 1 science drivers outlined below. This was the first time this science working group had convened and only a small group attended. Hence, the Level 1 science drivers are very much a reflection of the personal taste of those in attendance.

Having said this, out of the topics covered in the current SKA Science document (Taylor & Braun, 1998) and a few others that were discussed, we tried extremely hard to select *only* those topics which would be considered by others to be outstanding and unique applications of the SKA for Level 1 science. Particularly, we tried to point to the science that could drive the specifications of the SKA. All the others we placed into Level 2.

This document is not intended to be exclusive, but at the very least represents a starting point for discussion. As a group we felt that it is paramount the discussion of drivers should involve a much larger group, for a broader purview of the science possibilites offered by the SKA. It is clear that we must endeavour to include more people in future discussions of this nature. To this end, if anyone has any comments or wishes to contribute to the discussion in any way please do not hesitate to contact me at the above email address.

2 Science Drivers

2.1 Level 1

Sub-AU imaging of proto-planetary disks
The process of planet formation in dusty disks represents one of the key challenges in modern astrophysics and is of great interest to all. This is especially so since the detection of planets around solar-type stars. The SKA has the sensitivity to provide sub-AU imaging of the cold dust in these disks that will permit direct observation of disk structure. This will allow study of how planet formation affects disk structure e.g. the formation of disk gaps, the effect of planet migration. The SKA will be the **ONLY** observational facility that is currently being planned for the future that will be capable of producing high-fidelity images with brightness temperature sensitivity of around ~ 10 K *at mas resolution.*

Two other points worth mention concerning observations of dust: 1) dust opacity $\propto \lambda^{-\beta}$, where typically $\beta \sim 2$. Thus, at cm wavelengths the dust opacity is lower than at shorter wavelengths, which may be vitally important for observation of the very densest proto-stellar cores (high mass star formation regions?); 2) if the long wavelength spectrum $\propto \lambda^{-2}$ and the dust is optically thin, the implication is that the emission arises from grains of size $\sim \lambda$. Hence, emission at cm wavelengths implies cm-sized grains - *rocks* - an evolutionary stage in the formation of large orbiting bodies.

Normal Stars

Current radio observations of stars are limited, with few exceptions, to active stellar phenomena - circumstellar material arising from mass-loss from the underlying star (e.g. stellar winds, supernovae, jets) or non-thermal emission arising from strong magnetic fields (e.g. flare stars, active binary systems, X-ray binaries). With the SKA it will be possible for first time to dectect, and in some cases image, photospheric emission from "normal" (i.e main sequence, low mass) stars other than the Sun. Several $\times 10^4$ cool MS stars spanning a large range of mass and temperature (hence evolution) will be detectable. Thus, it will be possible to observe a range of phenomena that we readily observe on the Sun in a large sample of other stars and thoroughly explore the "radio solar-stellar" connection.

- magnetic field strengths, filling factors, electron density as a function of stellar type, rotation period
- high time resolution studies of flares, including micro-flares
- modulation of activity by stellar rotation.
- thermal emission from normal stars out to 50pc

Zeeman effect

Sensitivity at high resolution, combined with a high degree of polarization purity will give the SKA a unique capability to determine the nature of the magnetic field strength in many different astrophysical phenomena. In relation to stars, the structure of the magnetic field around proto-stellar objects in dense molecular cores and its role in the star formation and outflow processes comes to mind. The advantage of Zeeman observations in the radio regime is that the ratio of Zeeman splitting to the Doppler width of the line is proportional to wavelength, so at longer wavelengths for a given field strength the splitting is easier to observe.

With the idea of high resolution mapping of the magnetic field distribution, potential molecules for observing Zeeman splitting at the higher frequencies are CCS (11, 22 GHz) and SO (13 GHz). A high degree of polarization purity will be required for ability to measure percent polarization across the line profile.

2.2 Level 2

We felt that essentially most other topics related to stars should be Level 2, largely because it seems unlikely that these topics will drive the SKA specifications, rather take advantage fo the specs driven by other science. The list of potential science is neither exclusive nor prioritized - just the ones that those present discussed!

- Sub-AU imaging of thermal emission/jets in proto-stellar systems.
- High mass star formation, hyper-compact HII regions.
- Structure of circumstellar envelopes - relationship to stellar parameters, surface activity (observed at other wavelengths), stellar evolution.
- Stellar astrometry - sub-mas astrometry for parallax determination out to a few kpc - binary motions

- Supernovae - connection between turn-on and peak radio flux luminosity and potential cosmological distance determination (out to a few z)? Type Ia detection?
- et al.

3 Effect of Science Drivers on SKA Specifications

3.1 Brightness temperature, resolution and frequency

Sub-AU imaging of proto-planetary disk provides a starting point for discussing the effect of the science drivers on the array specifications, largely since the ability to attain a sensitivity of 10 K at a few mas seems to ensure a capability to address many (most?) other topics related to the imaging of thermal emission.

A typical proto-planetary disk has a radial temperature distribution that goes as

$$T(r) \sim 150\left(\frac{R}{\mathrm{AU}}\right)^{\frac{1}{2}}.$$

To image disk structure at radii similar to those of the Jovian planets in the Solar System, say out to 10AU ($T(10\ \mathrm{AU}) \sim 50$ K) from the central star, then we require brightness temperature sensitivity of ~ 10 K. Brightness temperature sensitivity is given by

$$\sigma_{\mathrm{T_B}} = 460\left(\frac{\sigma_{\mathrm{S}_\nu}}{\mu Jy}\right)\left(\frac{\mathrm{B_m}}{1000\ \mathrm{km}}\right)^2,$$

where σ_{S_ν} is the flux rms, and $\mathrm{B_m}$ is the maximum baseline length. For an 8-hr observation with a flux sensitivity of $\sim$ 20nJy in one polarization, $\sigma_{\mathrm{T_B}} \sim 10$ K can be attained with a maximum baseline of 1000 km.

To image disk structures such as gaps within the central few AU of the central star a requires sub-AU imaging capability. To attain such a high linear resolution demands long baselines. For objects at 200pc, a linear resolution of < 1 AU requires an angular resolution of better than 5 mas. At 22 GHz, a maximum baseline of 1000 km gives 3 mas resolution, attaining the required sub-AU resolution for objects within 200pc.

In dusty envelopes, at higher frequencies (40-50 GHz) dust emission dominates, whereas at 22 GHz free-free emission is more of a factor. Going to a higher frequency would shorten the maximum baseline length, but maintaining the flux sensitivity (or more precisely $\mathrm{A_{eff}/T_{sys}}$) will become difficult .

3.2 Addressing the current SKA specifications

- **$\mathbf{A_{eff}/T_{sys}}$:** naturally one would like this number to be higher (!), but that portends an even larger collecting area or lower $\mathrm{T_{sys}}$. It is important that this number holds at the highest frequency. If it decreases, the flux sensitivity degrades and maintaining a particular $\sigma_{\mathrm{T_B}}$ will require a decrease in baseline length. In turn, shorter baselines will demand a higher observing frequency to maintain a particular angular resolution. Study of trade-offs required?
- **Total frequency range:** For thermal processes need to attain as high a frequency as possible to take advantage of rising spectrum for SNR considerations. Capability for 22 GHz is very important - gives the required angular resolution with baselines of $\sim$ 1000 km. Also operation at 22 GHz provides access to spectral lines for high resolution Zeeman observations.

- **Imaging field-of-view:** The capability to image many, many sources simultaneously within the primary beam, allows statistically meaningful population studies - consider observations of complete stellar clusters; large numbers of proto-planetary systems within a star formation region etc.

  Though other SWGs will place more stringent demands on fov, larger fov is better here, certainly for population studies.

- **Number of instantaneous pencil beams:** No driver for more than one primary beam. Retaining the full sensitivity of the array within a primary beam is important.

- **Angular resolution:** A few mas - to attain sub-AU capability for objects out to 200pc. With maximum baselines of a few × 1000 km, can still attain sufficient brightness temperature sensitivity to effectively image thermal emission processes, though the ability to maintain $\sigma_{\mathrm{T_B}} \sim 10$ K at angular resolutions of a few mas is paramount (See also $\mathrm{A_{eff}/T_{sys}}$ above). This has an impact of array configurations - need a significant portion of the collecting area on long baselines.

- **Number of spatial pixels:** No driver.

- **Surface Brightness Sensitivity:** A capability to attain a brightness temperature sensitivity of at least 10 K, at a resolution of a few mas.

- **Instantaneous Bandwidth:** No driver, but wider bandwidth (with enough channels to avoid smearing) is better for continuum work. Used current spec to determine continuum sensitivity.

- **Clean Beam Dynamic Range:** No driver

- **Polarization Purity:** Capability set by case for Zeeman splitting. To be determined.

4 Specific Studies required

- Need to work out the trade-offs between frequency, baseline length and sensitivity (bandwidth, array configuration, assuming the current spec for $\mathrm{A_{eff}/T_{sys}}$) to maintain a capability for sub-AU imaging with $\sigma_{\mathrm{T_B}} \sim 10$ K. Leaving the array configuration aside, this is could be done relatively easily.

- Array configurations are an important consideration in order to maintain the desired sensitivity at the desired resolution. All SWGs have a vested interest in array configuration work.

- Need to work out the polarization purity required to determine a Zeeman split. Also, it would be good the angular resolution that could be attained. Anticipate that this work is of interest/concern to other SWGs.