

Continuous frequency coverage from SKA MID to ALMA

Tony Mroczkowski

European Southern Observatory (ESO)

7 Sept 2023





SKA sensitivity

- Due to the large collecting area, SKA-Mid and eventually SKA2 could feature the highest sensitivity for observations < 50 GHz.
- Figures from Braun, Bonaldi, Bourke, Keane and Wagg 2019 (<u>https://arxiv.org/abs/1912.12699</u>)
- NB: the gap from ~50-70 GHz is due to a 60 GHz oxygen line in the atmosphere.
- Of course, SKA-Mid Band 6 must be built for this to happen.





A few cases for continuous spectral coverage

Just a few thoughts...

- Continuous spectral coverage for:
 - cross-calibration
 - solar observations
 - complex organic molecules (COMs)
 - grain growth / size in planet formation
 - high-redshift searches (also true for moderately redshifted lines)
 - transient events
 - disentangling complex continuous emission in e.g. clusters



SKA solar observations

- Wavelength scales with height in the Sun's atmosphere (see image below, from Wedemeyer et al. 2016)
- SKA could probe the high chromosphere, towards the corona (e.g. see image on right, from Wedemeyer et al. 2022).







Lines from cold molecular gas

- COMs complex organic molecules like • glycine, formamide, etc.
- **Biological precursors?** •
- Fainter at lower frequency.

Line ratios probe the gas state



Figure 8: Spectrum of glycine simulated for the physical conditions and glycine abundance predicted for the hot corino IRAS16293-2422 B (see text for details). The glycine transitions covered by the high-frequency receivers of Band 6 are factors \sim 25-30 brighter than those covered within Band 5.



Figure 10: The physical structure of the TW Hya model (top), along with the resulting simulated spectra (bottom) of COMs of interest across SKA Band 5 (4.8–13.8 GHz) and the proposed Band 6 (15-50 GHz). Frequencies greater than $\sim 30 \text{ GHz}$ cover transitions up to 500 times stronger than those within Band 5, offering the best chance to detect and characterise these molecules in protoplanetary discs with the SKA.



Redshift searches

- Discontinuous coverage leaves gaps in the evolutionary history of the universe
- The SKA at low frequencies will cover neutral hydrogen in the early universe
- At lower redshifts (z<13, and especially near the peak in star formation), SKA Band 6 and ALMA are important for getting CO J(1-0), our best tracer for molecular hydrogen (H₂ does not emit lines).
- Other examples: mapping the nitrogen hyperfine structure line in the WHIM (e.g. Dochenko & Sunyaev 1984, SKA Memo 20-01)



Continuum

- Contributions to continuum emission are complicated
- The figure to the right, adapted from *Planck Collaboration 2015* and the Dickinson 2018 review, shows 4 "foreground" (fg) signals that "contaminate" the CMB signal (n.b. non-CMB people might not see these as contaminants).
- ALMA Band 1 (35-50 GHz) and Band 2 (67-116 GHz) are highlighted (this version was in the Band 2 paper; Yagoubov et al. 2020), though one can see the signals are most complicated in the 25-50 GHz range.

Continuous Coverage from SKA to ALMA, 7-Sept-2023

8







Exoplanets

- Thermal dust emission tends to grow as frequency to the power of ~2-3.5 (i.e. favoring shorter wavelengths)
- The maximum size of grains will determine a knee in the spectrum, and the spectral shape overall will enable model fits to the distribution of grains (see e.g. SKA Memo 20-01, where this figure is from).

Table 3: Disk polarization with SKA1-MID							
	HL Tau				IM I	IM Lup^3	
	$3 \mathrm{mm} \mathrm{p}$	ol ring ¹	Inner	Inner $ring^2$			
u	Flux	Time	Flux	Time	Flux	Time	
(GHz)	(μJy)	(hrs)	(μJy)	(hrs)	(μJy)	(hrs)	
13	0.2	500	0.2	500	0.3	330	
25	1.7	40	1.1	80	1.4	55	
35	4.6	9	2.6	28	2.9	23	

¹ ALMA 3mm polarization ring Kataoka et al. (2017) at a radius of ~ 60 au. The values derived are obtained extrapolating the 3 mm polarization using $\alpha = 3.0$ (Carrasco-González et al., 2019).

² Inner ring at a radius of ~20 au (Carrasco-González et al., 2019). The values derived are obtained extrapolating the 8 mm polarization using $\alpha = 2.5$ (Carrasco-González et al., 2019).

 3 Polarization extrapolated from the ALMA 0.87 mm image by Hull et al. (2018) assuming $\alpha=2.5$



Figure 7: Radiative transfer modelling of a planet forming within a protoplanetary disk, simulated using hydrodynamics with a decoupled dust component. Panels show frequencies and angular resolutions appropriate for (a) ALMA, (b) JVLA and (c) SKA1-MID. In order to achieve comparable angular resolution between the mm and cm regimes, SKA1-MID is required at frequencies ≥ 25 GHz (Hall & Ilee, in prep.)



Follow-up of transient events

THE ASTROPHYSICAL JOURNAL, 781:37 (21pp), 2014 January 20

- Numerous types of transient events are distinguishable using their radio to mm wave emission. I'll just give one example.
- Gamma ray bursts peak in the 10-100 GHz range in the first day after going off (see Perley et al. 2014, figure on right).
- Locating the peak and observing the evolution aids our physical interpretation. This also argues for wide instantaneous bandwidth.



Figure 10. Observations of the afterglow of GRB 130427A spanning from the low-frequency radio to the 100 GeV LAT bands, interpolated to a series of coeval epochs spanning from 0.007 days (10 minutes) to 130 days after the burst. Overplotted over each epoch is our simple forward+reverse shock model from standard synchrotron afterglow theory, which provides an excellent description of the entire data set, a span of 18 orders of magnitude in frequency and 4 orders of magnitude in time. The solid line shows the combined model, with the pale solid line showing the reverse-shock and the pale dotted line showing the forward-shock contribution. The "spur" at $\approx 10^{15}$ Hz shows the effects of host-galaxy extinction on the NIR/optical/UV bands. Open points with error bars are measurements (adjusted to be coeval at each epoch time); pale filled points are model optical fluxes from the empirical fit in Section 3.4. The inset at lower left shows a magnified version of the radio part of the SED (gray box) at t > 0.7 days.

SKA Band 6: observations of the thermal Sunyaev-Zeldovich (SZ) Effect

- Electron thermal motions impart a net shift to higher energies for a fraction of CMB photons passing through the cluster gas (via inverse Compton scattering).
- Image from Mroczkowski et al. 2019, SSRv, 215, 17.



SKA Band 6: observations of the thermal Sunyaev-Zeldovich (SZ) Effect

• Spectral dependence







SKA Band 6: observations of the thermal SZ Effect

- Yvette Perrott detailed this in the Band 6 science case (Memo 20-01).
- While the signal to noise is higher at higher frequencies for a given feature size (top plot), the uv space coverage matters (lower plot). This argues for wider frequency coverage to probe more scales.
- NB: Yvette did not assume the MeerKAT dishes would be upgraded with higher frequency receivers.
- I would advocate for consideration of very short spacings (i.e. Band 5B and Band 6 on the MeerKAT dishes).
- I would also advocate for consideration of complementary future facilities like the 50-m single dish AtLAST, which recover larger angular scales and will cover ~30-950 GHz at a much greater mapping speed than ALMA.



14.11 GHz is cyan, 23.75GHz is magenta, and 37.5GHz black





Example: ACA+ALMA constraints on the Bullet Cluster

- Modulo the lower frequency radio "contamination", the SKA Band 6 view will be closer to that of ALMA Band 3 (90 GHz) observations, which offered a clean view of the shock seen in x-ray.
- Images are from Di Mascolo, Mroczkowski, et al. 2019





Example: The Bullet cluster at lower frequencies

- Low frequency radio emission seen by MeerKAT in L-band
- Observations were first published in Sikhosana et al. 2023 (<u>https://ui.adsabs.harvard.edu/abs/202</u> <u>3MNRAS.518.4595S/abstract</u>).
- These figures are from Botteon et al. 2023 (<u>https://ui.adsabs.harvard.edu/abs/202</u> <u>3A%26A...674A..53B/abstract</u>)





Example: The Bullet cluster

Comparison of the MeerKAT L-band to Chandra X-ray. Both images have point sources removed

(Botteon et al. 2023; https://ui.adsabs.harvard. edu/abs/2023A%26A...6 74A..53B/abstract)





Example: The Bullet cluster

 Sikhosana et al. 2023 provide an in-band spectral index map (<u>https://ui.adsabs.harvard.edu/abs/</u> 2023MNRAS.518.4595S/abstract).





Conclusions?



- cross-calibration
- solar observations
- complex organic molecules (COMs)
- grain growth / size in planet formation
- high-redshift searches (also true for moderately redshifted lines)
- transient events
- disentangling complex continuous emission in e.g. clusters

The results will depend on array configurations, compact spacings, bandwidth, and ultimate performance.

18 Continuous Coverage from SKA to ALMA, 7-Sept-2023

