Star Formation at High Angular Resolution
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Star Formation with Future Millimetre- and Radio-Interferometers

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Abstract. The Low Frequency Array (LOFAR), the Atacama Large Millimetre Array (ALMA), and the Square Kilometre Array (SKA) will be the largest and most capable aperture synthesis facilities of the next few decades. The advances in our knowledge of star formation that ALMA will permit are well known to the star formation community, but the potential of the SKA has so far attracted less attention. I will outline the star formation science cases of these upcoming facilities, with an emphasis on the SKA.

1. Introduction

Over the next two decades, large new interferometric telescopes will come into operation which will together cover essentially the entire ground-based radio-to-submillimetre window (Figure 1). These new mega-facilities are the Low Frequency Array, the Square Kilometre Array, and the Atacama Large Millimetre Array. Covering five decades of frequency from 10 MHz to 1 THz with unprecedented sensitivity and angular resolution, these upcoming instruments are likely to dominate observational research in their respective wavebands well into the mid-21st century. They will also firmly establish aperture synthesis as an essential component of the observational astronomer's toolkit. Since all of these instruments will operate as "full-service" facilities intending to deliver near-final science data sets to the investigator, their user community will likely range well beyond the traditional interferometer community.

The scientific potential of ALMA for high resolution studies of star formation has been highlighted at the conference *Science with the Atacama Large Millimeter Array* (Wooten 2001) and in this symposium. The star formation science case for the SKA has not yet been widely promoted within the astronomical community, and the main intent of this contribution is to highlight that part of the still-evolving SKA science case.

1.1. LOFAR - The Low Frequency Array

LOFAR is a project of ASTRON (Netherlands), MIT (USA), and the Naval Research Laboratory (USA). It will operate in two low frequency bands 10−90 MHz and 110−240 MHz (avoiding the commercial FM broadcasting band). It will be an aperture synthesis array composed of phased array stations arranged in a

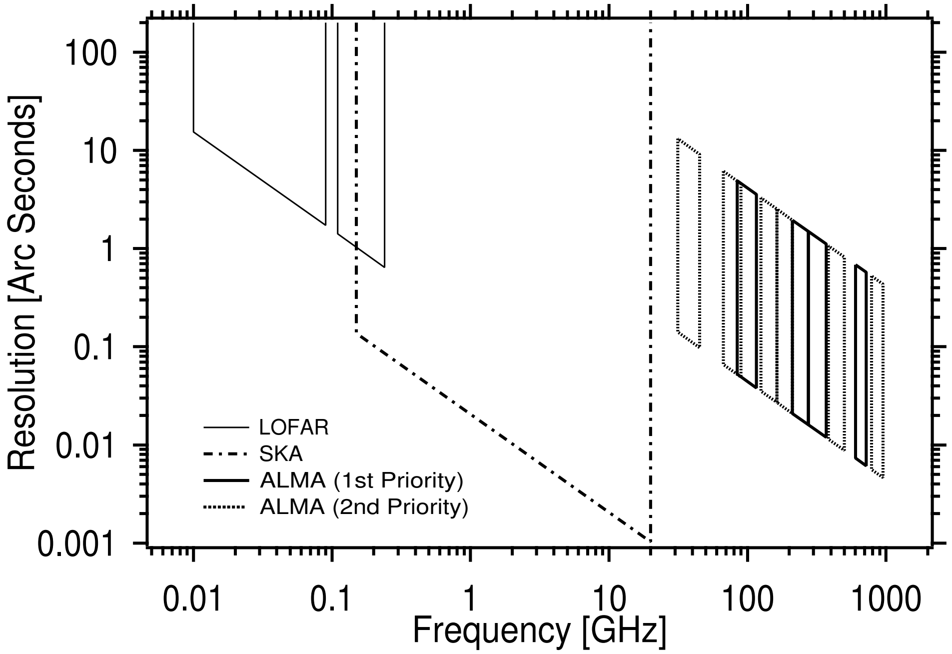

Figure 1. New millimetre- and radio-interferometers will cover 5 decades of frequency in the ground-based radio windows. A maximum operating frequency of 20 GHz and a maximum baseline of 3000 km is assumed for the SKA. ALMA has provisions for receivers in 10 bands, 4 of which will be implemented initially.

scale-free log-spiral pattern with maximum baseline of 360 km. In each frequency band there will be ~13000 receptors distributed among the ~100 stations; in the lower band the receptors will be individual dual polarization dipoles and in the upper band a receptor will be composed of a beamformed 4×4 array of dual polarization dipoles. LOFAR will operate in interferometric and phased array modes and be capable of sub-array operation and multiple beams. The LOFAR site has not yet been determined, but locations in Australia, Europe, and North America are being considered. Present plans call for LOFAR to begin initial operations in 2006 with full operations to come in 2008.

Current low frequency facilities are severely limited in collecting area, angular resolution, uv coverage, frequency range, and instantaneous bandwidth. LOFAR will mark an important leap in all of these capabilities at metre wavelengths. LOFAR's main science goals are not very relevant to the topic of this symposium, but LOFAR does have potential capabilities in the related field of direct detection of extrasolar planets: it might be able to detect the sporadic cyclotron maser radio emission of nearby extrasolar gas giant planets (Farrell et al. 1999; Bastian et al. 2000).

1.2. SKA - The Square Kilometre Array

In the centimetre-wavelength frequency band, there are a number of interferometric facilities which provide various combinations of sensitivity, angular resolution, and field of view, such as the VLA, MERLIN, and the VLBA. The Square Kilometre Array, an interferometric array with longest baselines up to several thousands of kilometres, will have two orders of magnitude greater sensitivity at centimetre wavelengths than any current instrument or planned upgrades (Table 1; Figure 2). A consortium of groups from several countries are at present researching various technologies for implementing the SKA (Table 2), with a decision presently expected around 2007, and construction likely to begin after 2010. Several locations around the world have been formally proposed as possible SKA sites, including Australia, China, North America, and South Africa.

Table 1. A subset of the current “strawman” design goals for the SKA.

Effective collecting area	1×10^6 m^2
System temperature	50 K
Total frequency range	0.15 to 20 GHz
Imaging field of view	1 square degree at 1.4 GHz
Number of instantaneous pencil beams	100
Maximum primary beam separation	1° at 1.4 GHz
Maximum primary beam separation (low ν)	100°
Angular resolution	$0.1''$ at 1.4 GHz
Number of spectral channels	10^4
Number of simultaneous frequency bands	2
Imaging dynamic range	10^6 at 1.4 GHz
Polarization purity	−40 dB

Table 2. Proposed technology pathways to the SKA.

Concept	Development group
Aperture plane arrays	European SKA Consortium
Cylindrical reflectors	Australian SKA Consortium
Large adaptive reflectors	National Research Council of Canada
Large spherical reflectors	Chinese Academy of Sciences
Large-N small-D arrays	Indian SKA Consortium
Large-N small-D arrays	United States SKA Consortium
Luneburg lens arrays	Australian SKA Consortium

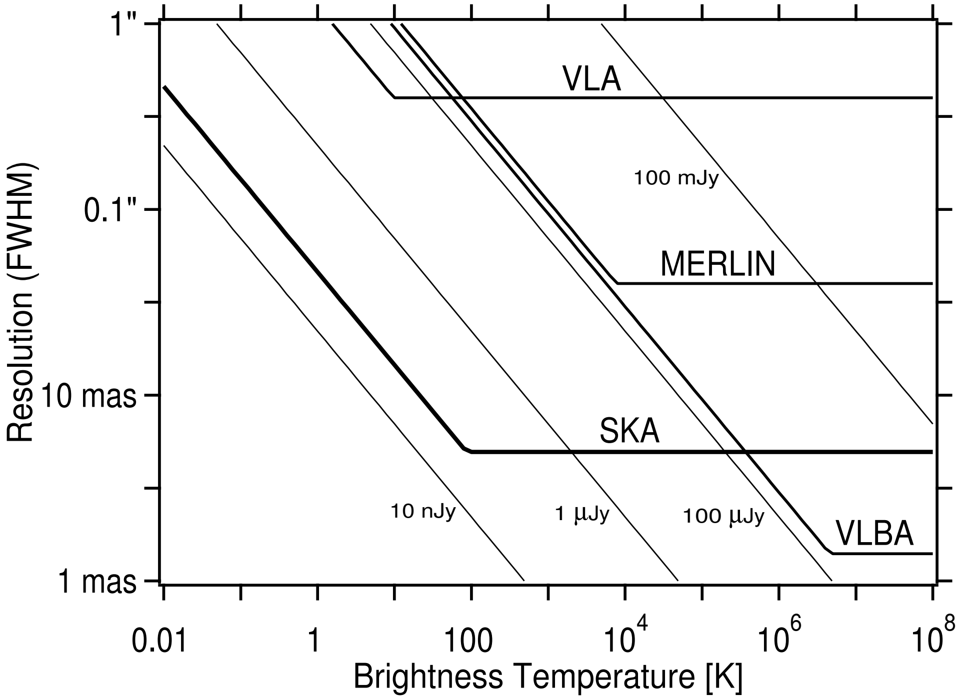

Figure 2. The angular resolution versus RMS brightness temperature sensitivity diagram occupied by various centimetre-wave interferometers. Indicated instruments occupy the region to the upper left of the heavy solid lines. Thin solid lines are loci of constant RMS flux sensitivity. Observing frequency is 5 GHz, integration time is 12 hours, and polarization is Stokes I.

1.3. ALMA - The Atacama Large Millimetre Array

Unlike metre- and centimetre-wavelength astronomy, (sub)millimetre astronomy has until very recently been dominated by single-dish instruments. A number of (sub)millimetre interferometers are now in operation or under development (CARMA, IRAM PdB, Nobeyama Millimetre Array, SMA), but the Atacama Large Millimetre Array will dwarf these facilities once it begins full science operations in 2012. A partnership between North America (USA and Canada) and Europe (ESO and Spain) with possible future Japanese participation, ALMA will consist of 64 12 metre diameter telescopes located at Llano de Chajnantor on the Chilean altiplano (Table 3). It will have unparalleled sensitivity and resolution at (sub)millimetre wavelengths, and has provision for covering all of the atmospheric windows between 31.3 and 950 GHz. The large number of baselines, coupled with a flexible reconfigurable array design, will permit good uv coverage over a large range of angular resolutions.

Table 3. Design parameters of ALMA.

Total collecting area	7200 m^2 (64 12 m dishes)
Total frequency range	31.3 to 950 GHz in 10 bands
Instantaneous field of view	$20''\lambda$[mm] (FHWM)
Baseline extent	$0.15 \leq \mathrm{B} \leq 14$ km
Maximum angular resolution	$0.2''\lambda$[mm]/B[km]
Number of simultaneous frequency bands	1
Number of spectral channels	4096×8 IFs = 32768
Instantaneous bandwidth	16 GHz

2. Star Formation with ALMA

The study of star formation at high angular resolution within our galaxy is a major theme of the ALMA science case, and there is not space here to do full justice to what ALMA will contribute. The following discussion will only touch upon some central themes in a qualitative way: I refer the reader to Wootten (2001) and to presentations made at the conference "Star Formation Near and Far: the ALMA Promise" (available online at `http://www.arcetri.astro.it/~elba03`) for much more extensive discussions of how ALMA will revolutionize the observational study of star formation.

Direct study of protostellar collapse motions is very difficult with current (sub)millimetre instruments due to sensitivity and resolution limitations. Most unambiguous detections of infall from line spectroscopy have been limited to high mass rather than low mass objects (Di Francesco et al. 2001). Detected through absorption measurements, interpretation of the line profiles can be difficult: observations of brighter lines of high optical depth complicates the radiative transfer (self-absorption), whereas absorption against the protostellar/disk continuum is at present limited to rather bright sources. ALMA should be able to detect infall motions in optically thinner lines againsti continuum sources much weaker than those currently detectable, and map them at high resolution, e.g., across the face of an extended hot accretion disk.

Since infall and outflow seem to be simultaneous processes in protostellar objects, there can be confusion in line observations of outflowing and infalling gas. The problem of outflow versus infall is an important one, as the interaction between the two may influence the final stellar mass. ALMA's resolution may be able to disentangle the two and detect evidence of outflow-infall interaction, such as shocks or chemical differences. The neutral/ionized winds that sweep up and accelerate molecular jets and outflows may transfer angular momentum outward, and ALMA may thus be able to measure rotation in the molecular jet component. It may also be able to detect the imprint on the dynamics and chemistry of molecular jets of transient and/or time variable events triggered by events occuring very close to the accretion disk/protostar. ALMA may have the sensitivity to detect the extremely weak outflows which might be driven by proto-brown dwarfs or other sub-stellar objects (Wolk & Beck 1990). High resolution coupled with high dynamic range imaging will be needed to distinguish the weak outflows of sub-stellar objects from the stronger outflows of protostellar objects in binary systems.

Study of the structure, dynamics, evolution, and chemical evolution of protostellar and protoplanetary disks will be a major science industry with ALMA. It should be possible to detect mass concentrations as small as a few Earth masses in the dust continuum at the distance of nearby star formation regions (Evans 2001). Young proto-Jovian planets may be detectable at ~ 1 kpc. The evolution of planet-forming disks may be directly observable with ALMA (Wolf & Klahr 2002). Jovian-class planets will clear out gaps in disks, and ALMA may be able to see these direct evidences for planet formation (Wolf et al. 2002).

3. Star Formation with the SKA

Centimetre-wavelength interferometers, especially the VLA, have long played an important role in high resolution studies of star formation, complementing observations made in the(sub)millimetre and far-infrared. The gain in angular resolution and sensitivity afforded to us by the SKA will permit qualitatively new types of observations to be made of Galactic star formation. I will not in this paper discuss SKA's considerable capabilities in studying extragalactic star formation in this paper; see Taylor & Braun (1999). In the following subsections I present a few of the more fundamental contributions to star formation at high angular resolution which the SKA will deliver.

3.1. Protoplanetary Disks

The formation of stars and the developmnent of planetary systems are both intimately tied to the presence and evolution of circumstellar disks. Both molecular spectral line and dust continuum emission can be used to study disks, but at the highest resolutions, spectral line observations of disks will be very difficult even for ALMA (Evans 2001). Although the raw sensitivity of the SKA for continuum observations far outstrips ALMA, the steep spectral dependence of the dust emission ($\propto \lambda^{2+\beta}$, with the dust opacity parameter usually $1 \lesssim \beta \lesssim 2$) means that ALMA will be one to two orders of magnitude more sensitive to dust emission than the SKA at the same resolution in the same observing time. However, in order to obtain resolutions of ≈ 10 mas (~ 1 AU at 150 pc), ALMA must observe at its highest frequencies where the dust emission may be optically thick. ALMA may therefore be limited in its ability to investigate the inner regions of protoplanetary disks in the "habitable zone" of solar systems or to probe into the very densest protostellar cores.

The dust emission at the lower frequencies where SKA will operate will be weaker (and possibly contaminated by free-free emission), but will almost certainly be optically thin. The SKA has higher resolution, ≈ 1 mas (~ 0.1 AU at 150 pc). The combination of low optical depth and sub-AU resolution makes SKA the best instrument to probe the highest-opacity regions and disks in the regions of terrestrial-type planet formation, and to study the effects of planet formation and migration on disk structure and evolution. Centimetre-wave emission from dust is important too as it provides clues to the evolution of dust grains in protoplanetary disks: a dust spectrum at low frequencies

$\propto \lambda^{-2}$, if optically thin, would imply that the emitting dust grains were of size $\sim \lambda \sim 1$ cm. Centimetre-wave observations can thus track the early evolution of planet-building processes in disks.

It should be noted that the presence of optically thick dust emission at (sub)millimetre wavelengths will also affect molecular spectral line observations by ALMA at the same wavelengths: spectral line emission emanating from within the optically thick dust surface will be heavily attenuated. This will be a limiting factor for attempts by ALMA to probe spectral lines deep inside dusty regions.

3.2. Mass Outflows

Strong mass loss occurs during star formation, in which processes occuring very near the protostellar object (accretion, rotation, magnetic fields) drive large scale bipolar outflows of mass. These flows are driven by strong ionized and/or neutral atomic winds which are formed and collimated on AU or sub-AU scales. The SKA will be the most capable telescope for studying protostellar winds and jets on these size scales.

Most deeply embedded (Class I and 0) protostellar objects have centimetre-wave thermal emission produced by ionized winds or jets, but only a few have been resolved (Anglada 1996), and current instruments do not trace the ionized flows sufficiently far from the base of the jet to connect them to the optically visible jet structures (Reipurth et al. 1999). It is thus difficult to associate short timescale variations in optical jets with episodic events at the base of jet due to, for example, variable accretion or disk instabilities. Proper motions of the order of $0.1'' \ \mathrm{yr}^{-1}$ in the radio continuumi jets have been detected in only a few systems (Rodríguez et al. 1989; Martí et al. 1998), and current instruments with the resolution and sensitivity to follow the evolution of thermal jets (the VLA, VLBA) can observe only the nearest, fastest, and brightest jets. The VLA requires observations spaced over a ~ 10 yr period in order to confirm motions of $0.1'' \ \mathrm{yr}^{-1}$, while the brightness temperature sensitivity of the VLBA is low. The SKA, however, with a combination of high resolution and high brightness temperature sensitivity, will be capable of single-epoch imaging of $T_{\mathrm{B}} \sim 10^3$ K jets at 10 mas resolution (Figure 2), which will permit high-resolution time-resolved studies of protostellar astrophysical jets.

Magnetohydrodynamical forces are thought to drive jets, but it is unclear whether these forces originate in the protostellar and/or accretion disk magnetic fields and what the geometry of the fields are. The resulting jets transport significant angular momentum, so mapping the rotational velocity fields of jets should throw light on their origin. Velocity field mapping in optically visible ionized jets is becoming possible (Bacciotti et al. 2002), but it is most important that velocity fields can be mapped in the acceleration and collimation regions of the flow which are only observable at radio wavelengths. This mapping might be possible in atomic recombination lines using the SKA (Hoare 2002).

Neutral atoms may be the kinematically dominant component of protostellar jets/winds, particularly in low mass objects. However, direct detection of neutral atomic protostellar winds by means of the HI 21 cm line has been limited to essentially only two of the ~ 200 known molecular outflows (Giovanardi et al. 2000). These observations, made using Arecibo and the VLA, are plagued by confusion, sensitivity, and angular resolution limitations. The SKA, with two orders of magnitude better angular resolution and sensitivity than the VLA when making 21 cm line observations, will be the only instrument capable of making further progress in the observational study of neutral stellar winds which drive molecular outflows.

3.3. Protostars

The wide field of view, multi-beaming capability of the SKA will allow large scale simultaneous monitoring of highly variable radio sources in star formation regions. Weak-lined T Tauri stars (Class III) are often seen to have strongly variable and polarized radio emission characteristic of non-thermal emission from electrons in large scale magnetic structures. Classical T Tauri stars (Class II objects) and embedded Class I objects have been rarely detected in this way (Ray et al. 1997; Feigelson et al. 1998), and there are no detections yet of non-thermal emission from Class 0 protostars. It would be surprising if the lack of detection were due to lack of activity in these younger objects (Tsuboi et al. 2001). It is more likely that absorption by the partially ionized winds and jets of these objects is attenuating the nonthermal emission. However, if magnetic structures sometimes extend beyond the absorbing blanket of ionized wind, the high sensitivity and angular resolution observations may be able to detect the time-variable polarized emission in the magnetospheres of these most deeply embedded objects.

3.4. Young Brown Dwarfs

Brown dwarfs are substellar objects with masses ($< 0.08\ \mathrm{M_P}$) too low for stable core hydrogen burning but distinguishable from giant planets by their ability to burn deuterium in early life. There are now numerous confirmed and candidate brown dwarf detections: older objects in the field and younger objects in star formation regions. Although it is not yet clear if brown dwarfs form like stars in cloud core collapse or like planets in protoplanetary disks, there is evidence of T Tauri-type accretion activity in young brown dwarfs (Jayawardhana et al. 2003) and of circum-brown dwarf disks (Pascucci et al. 2003). Given the similarities between young brown dwarfs and T Tauri stars and late M-dwarfs, nonthermal radio emission from the former would be expected. The only known radio-emitting brown dwarf is the nearby (5 pc) object LP 944−20 (Berger et al. 2001), with flaring/non-flaring fluxes of 2 mJy/80 μJy respectively. At the distance of the nearest star formation regions (150 pc, hence fluxes 2 μJy/0.1 μJy), detection of objects with radio properties similar to LP 944−20 will require the sensitivity of the SKA (note that LP 944−20 is a relatively old brown dwarf and the origin of its radio emission is uncertain).

3.5. Zeeman Imaging

The Zeeman effect in molecular spectral lines is the only direct way to measure the (line of sight component) intensity $B_{||}$ of magnetic fields in the dense interiors of star-forming clouds. The frequency splitting between polarized Zeeman line components, $\Delta\nu_{\rm z} = 2{\rm Z}B_{||}$, is generally much less than the Doppler width $\Delta\nu_{\rm d}$, and so splitting is generally not directly detected but indirectly by measuring the polarized spectra (Crutcher 2001). Few molecules have large Zeeman splitting factors ($Z > 0.3$ Hz μG^{-1}), limiting the number of useful molecular lines for magnetic field measurements. However, a number of useful lines are found at SKA frequencies (Table 4). Zeeman measurements demand both extremely high sensitivity and polarization purity in the observations, both of which SKA should be able to deliver. The Zeeman-sensitive molecules CCH, CN, and SO will be available to ALMA at millimetre wavelengths, but there are a number of advantages to making Zeeman observations with the SKA. Firstly, SKA's wide instantaneous field of view will allow fast large scale mapping of clouds. Secondly, since $\Delta\nu_z/\Delta\nu_d \propto \nu^{-1}$ for a given value of Z, the ratio of Zeeman splitting to Doppler line width is more favourable at lower frequencies.

Table 4. Zeeman-sensitive line transitions potentially available to the SKA. Note that the splitting factor Z is expressed in velocity rather than frequency units.

Molecule	ν [GHz]	Splitting [km s^{-1} G^{-1}]	Regime
CCS	11.1	22	Pre-protostellar cores
CCS	22.3	10	Pre-protostellar cores
SO	13.0	45	Hot dense cores
SO	30.0	17	Hot dense cores

4. Conclusions

Given the valuable role played in the past by centimetre-wave facilities in the study of star formation, it is not surprising to find that there are compelling reasons to advocate SKA as an important complement to ALMA in the new high resolution interferometric era. This complementarity can only be guaranteed if the still-evolving technical specification of the SKA takes account of the requirements of the centimetre-wave star formation case. Some key requirements might include high frequency operation (up to ~ 30 GHz), high brightness temperature sensitivity on long baselines, good imaging capability over a wide range of angular resolutions, a powerful and flexible spectral line capability, and excellent polarization capability. Locating the SKA where it will have good overlap in sky coverage with ALMA may also be desirable. A greater participation of the star formation community in science planning for the SKA should be strongly encouraged.

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