Tomography of Galactic star-forming regions and spiral arms with the Square Kilometre Array

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Very Long Baseline Interferometry (VLBI) at radio wavelengths can provide astrometry accurate to 10 micro-arcseconds or better (i.e. better than the target GAIA accuracy) without being limited by dust obscuration. This means that unlike GAIA, VLBI can be applied to star-forming regions independently of their internal and line-of-sight extinction. Low-mass young stellar objects (particularly T Tauri stars) are often non-thermal compact radio emitters, ideal for astrometric VLBI radio continuum experiments. Existing observations for nearby regions (e.g. Taurus, Ophiuchus, or Orion) demonstrate that VLBI astrometry of such active T Tauri stars enables the reconstruction of both the regions' 3D structure (through parallax measurements) and their internal kinematics (through proper motions, combined with radial velocities). The extraordinary sensitivity of the SKA telescope will enable similar *tomographic mappings* to be extended to regions located several kpc from Earth, in particular to nearby spiral arm segments. This will have important implications for Galactic science, galactic dynamics and spiral structure theories.

1. Introduction

Very Long Baseline Interferometry at radio frequencies (e.g. Thompson et al. 2007) can readily provide astrometric accuracies of order 10 micro-arcseconds (μas) or better, for compact radio sources of sufficient brightness ($T_b \approx 10^7$ K). This enables the determination of trigonometric parallaxes with an accuracy of a few percent for any source within a few kpc (for instance, a 10 μas astrometric accuracy translates to a 2% parallax accuracy at 2 kpc). Similarly, proper motions can be measured to an accuracy of 0.2 km s^{-1} in one year at a distance of 2 kpc. As a consequence, **radio VLBI measurements have the potential to provide distances accurate to better than a few percent, and tangential velocities accurate to better than a few tenths of a km s^{-1} for any source within a few kpc** (Reid & Honma 2014). The GAIA space mission is expected to deliver similar results, and will do so for many millions of stars (de Bruijne 2012). However, radio VLBI observations have the distinct advantage that they are not affected by dust extinction. Thus, they can be used to complement GAIA for sources that are either deeply embedded within dusty regions, or located behind a large column of line-of-sight dust (or both). Star-forming regions are clearly in this situation, and are therefore prime targets for VLBI astrometric observations.

The astrometric potential of radio VLBI observations can only be realized if the intended targets are detectable. As mentioned earlier, this requires the brightness temperature to be of order 10^7 K (Thompson et al. 2007), and effectively restricts the pool of potential targets to non-thermal emitters.[1] In star-forming regions, there are two classes of sources that meet the brightness criteria: masers and chromospherically active young stars. Masers (hydroxyl, water, methanol, and to a lesser extent silicon monoxide) are commonly found in high-mass star-forming regions (Bartkiewicz & van Langevelde 2012) and can be extremely bright. This makes them ideal tracers to map the distribution of high-mass star-forming regions across the Milky Way (Reid et al. 2014; Green et al. 2015). Chromospherically active young stars, on the other hand, are often radio sources thanks to the gyration of relativistic electrons in their strong surface magnetic fields (Dulk 1985). This results in continuum cyclotron, gyrosynchrotron, or synchrotron emission depending on the energy of the gyrating electrons. This emission is normally confined to regions extending only a few stellar radii around the stars, and therefore remains very compact even in the nearest star-forming regions (4 $R_\odot \equiv 50$ μas at 300 pc). We note that for this mechanism to operate, a strong magnetic field (kGauss) must exist, and this normally requires the dynamo process to operate within the young star. This, in turns, requires the star to be convective, so only **low-mass** young stars are expected non-thermal radio emitters. There are, however, some exceptions to this rule (Loinard et al. 2008; Dzib et al. 2010).

Since masers and magnetically active low-mass young stars can both be used for VLBI astrometric observations, it is useful to consider their relative merits. Masers are typically much brighter and can therefore be detected much farther than magnetically active young stars. On the other hand, active young stars are much more ubiquitous. First, they do exist in regions of low, intermediate, and high-mass star formation, whereas bright, steady masers are largely restricted to high-mass regions. A limited number of masers have been identified in association with low-mass stars but they are typically of lower luminosity (Kalenskii et al. 2010) than those found toward high-mass star formation regions. Second, tens or hundreds of magnetically active low-mass young stars might

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[1]For instance, a compact HII region with a brightness temperature of order 10^4 K is undetectable with a VLBI array.
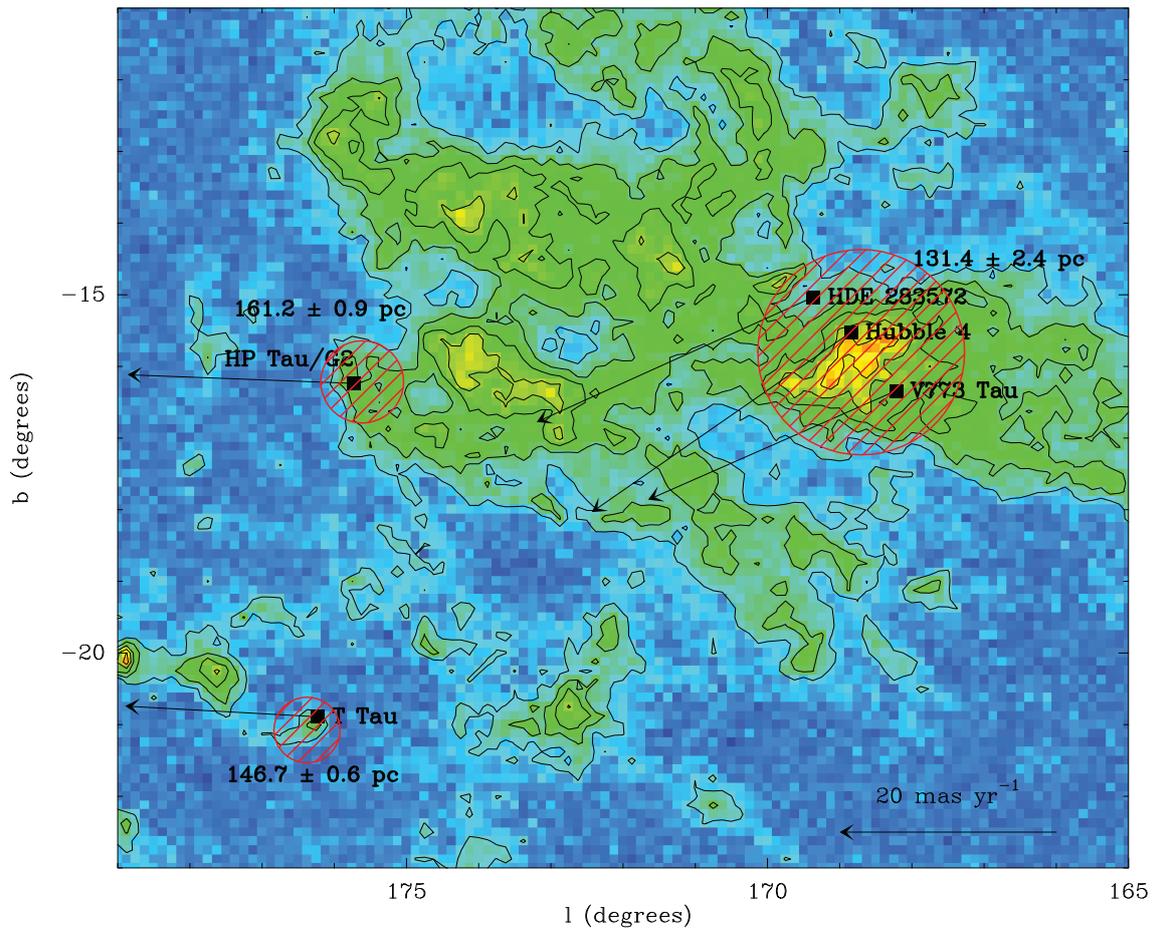
Figure 1: Positions, distances, and proper motions of Hubble 4, HDE 283572, V773 Tau, T Tau, and HP Tau/G2 superposed on the CO(1-0) map of Taurus from Dame et al. (2001). Adapted from Loinard et al. (2007); Torres et al. (2007, 2009, 2012).

be present in a high-mass star-forming region where only a few strong maser spots exist. For instance, only a few maser sources are known in the Orion region (Gaume et al. 1998) where we have recently detected well over 50 magnetically active young stars in moderately deep VLBA observations (M. Kounkel et al., in preparation). A very interesting application of this ubiquity is that distances and proper motions can be measured to stars distributed across a given region, and the three-dimensional structure and kinematics of the region can be reconstructed. This has recently be exemplified in the case of the Taurus star-forming region (Torres et al. 2007, 2009, 2012) thanks to multi-source VLBA observations. As Figure 1 shows, the young stars located to the west of the Taurus regions are at a common distance of 130 pc, and share similar proper motions. Measurements from the literature show that they also have similar radial velocities. The stars to the east and south of the complex, on the other hand, are significantly farther (145-160 pc) and have different proper motions and radial velocities. Although based on a very limited number of targets, this example demonstrates that multi-source VLBI observations enable *tomographic mappings* of individual star-forming regions. In this contribution, we build the case for extending such observations using VLBI with the SKA to regions farther from Earth, and particularly to nearby segments

of spiral arms.

2. Scientific Rationale and synergy with other projects

Thanks to its enormous collecting area, the SKA will provide unprecedented sensitivity for radio continuum observations. As will be shown below, this will enable tomographic mappings with unprecedented accuracy of nearby regions such as Orion in a fairly modest amount of telescope time, even during the SKA1-MID phase. Such detailed reconstruction of the 3D structure and kinematics of individual star-forming regions will provide important tests for models of star-formation and early stellar evolution. For instance, a complete 6D (3 spatial + 3 velocity components) description of the young stellar population in a given cluster could be used to test theoretical models such as those proposed by Hartmann & Burkert (2007) for Orion. Similarly, very accurate HR diagrams made possible by accurate distances could be used to constrain pre-main sequence evolutionary models (see Loinard et al. 2011, for details). It will also be interesting the characterize the magnetospheric activity on young stars (Forbrich et al. 2011) by statistically examining the relation between evolutionary stage, mass, and magnetic activity.

For a full description of the 3D structure of star-forming regions, one has to consider, apart from the young stars and star-forming regions, also the molecular cloud. It impossible to measure parallaxes to extended structures such as clouds, but one can unravel the cloud through its dust content, assuming a ratio between the gas and the dust. The advantage of the dust is that we can measure its optically thin emission in the infrared to sub-millimeter and at the same time that dust will redden the stellar light in the optical and the near-infrared. Stars with accurate distances and stellar types can thus be used as pinpoints to reconstruct the cloud structure by measuring their reddening (for example Knude 2009). As clouds can have extents of several tens of parsecs, the distance accuracies have to be high, better than $\sim$10 pc, to obtain a detailed structure of the cloud.

Imposing a 2% parallax accuracy requirement, GAIA will deliver astrometry of B-G dwarfs out to 3–1 kpc (for B dwarfs) and 850–200 pc (G dwarfs) for visual extinctions of 1 to 10 mag, respectively. Later, but more common spectral types, such as M stars, have their astrometry limited to the very nearby stars only (200–50 pc for A_V of 1-10 magnitudes). Herschel maps show that the nearby low-mass clouds have most of their extent at $A_V < 10$ mag (see e.g., Peretto et al. 2012, Rygl et al. 2013, Kirk et al. 2013). Hence, combining VLBI and GAIA astrometries, we can measure both the low-density and the high-density extent of nearby molecular clouds, and have a complete 3D picture of the stars *and* the cloud, and the kinematics of the young and main sequence stars of stellar complexes. With early type stars (O-A) such studies could be extended out to the nearby segments of spiral arms.

With the full SKA2, VLBI tomographic mappings could be extended to the nearest spiral arm segments at 2–3 kpc (see Section 4.2). Spiral arms are likely to have a width of at least several hundred parsecs (several times the size of a massive star-forming region like Orion), so a parallax accuracy of order 1% at 2.5 kpc would easily reveal the depth of a spiral arm segment. Thus, the tomography proposed here would reveal the inner structure of Galactic spiral arms in unprecedented details, as well as the 3D motions of the young stars along and across the arm. This could be directly compared with the predictions of theoretical models (e.g. Bertin & Lin 1996), and would represent a major contribution to the study of the dynamics of galactic disks in general. It is

important to stress that the level of details that would be achieved through this type of observations could not be obtained in any external galaxy for the foreseeable future, nor in our own Galaxy with GAIA due to a combination of crowding and dust obscuration.

There is a clear synergy between the tomographic mappings proposed here and the maser and pulsar astrometric observations described in Green et al. (2015) and Han et al. (2015).

3. VLBI observations incorporating the SKA and strategies for astrometry

In all that follows, we will assume that the observations are made at a frequency of order 6 GHz, i.e. at the lower frequency end of SKA Band 5. We consider a VLBI array consisting of 70% of the SKA1-MID collecting area phased-up, and a further 10 other stations with characteristics similar to those of an individual SKA1-MID antenna. Assuming a 1 GHz bandwidth (the sum of two orthogonal polarizations; implying a data rate of 4 Gbps per antenna), we obtain an rms per baseline (phased SKA1-MID to single antenna) in the continuum of 220 μJy in 60 seconds and 97 μJy in 5 minutes. We estimate the image sensitivity by dividing the baseline sensitivity by $\sqrt{N_{ant}-1}$ and applying no weighting, since baselines to the phased SKA1-MID are so much more sensitive than those between the rest of the antennas in the array. The corresponding continuum image sensitivities (1σ) for 1 and 5 minutes are 97 and 31 μJy respectively.

A crucial ingredient for accurate astrometric measurements with the SKA is the presence of nearby calibrators, ideally within the primary beam of the SKA antennas, so that with multiple beams from the phased SKA1-MID we can simultaneously observe both the targets and the background quasar. The VLA was used by Fomalont et al. (1991) to characterize the faint source population at 5 GHz and found that N, the number of sources per square arc minute stronger than flux density S (where S is in μJy) is given by

$$N(S) = (23.2 \pm 2.8)S^{-1.18 \pm 0.19}.$$

The fraction of faint 5 GHz sources which are compact on VLBI scales has (to our knowledge) not been measured but it is safe to assume that it is higher than 20% (the fraction of faint source population detected in deep VLA observations at 1.4 GHz that are compact on VLBI angular scales (Garrett 2005)). Taking all this into account, we predict 3 sources in the primary beam stronger than 150 μJy and perhaps one source stronger than 500 μJy.

The astrometry precision for a single epoch VLBI observation is given by

$$\theta_{ast} = \frac{\theta_{beam}}{2 \times \text{SNR}\sqrt{N_{cal}}},$$

where N_{cal} is the number of calibrators. For a maximum baseline length of 8000 km we have a synthesized beam of 1.2 mas (3.1 mas for a 3000 km baseline). To achieve an astrometric accuracy of 5 μas after 4 epochs (which would yield distances accurate to 1% at 2 kpc), we will need a per epoch accuracy of around 10 μas (including systematic components of astrometric calibration). We see from above that we need the product $2 \times \text{SNR} \times \sqrt{Ncal}$ to be approximately 120 if we have an 8000 km baseline length or 310 if the maximum baseline length is shorter. For 150 μJy calibrators we then need an SNR of around 30 (3 in-beam calibrators), which implies on-source time per epoch of 4 hours per source. For a 500 μJy calibrator we need an SNR of around 60 (only 1 in-beam calibrator), which implies an on-source time per epoch of 1 hour.

4. Staged approach to tomographic mappings of star-forming regions with the SKA

4.1 SKA1-MID

It is clear from the previous section that the SKA will have the potential of carrying out detailed tomographic observations of regions of star-formation located at distances of up to several kpc. We propose to realize this potential through a staged approach. In an initial phase, we would focus on a nearby region (e.g. the Orion Nebula Cluster – ONC) to demonstrate the capabilities of VLBI astrometric observations with the SKA1-MID. We would observe at least 200 young stars distributed across the complex (we know from VLA and VLBI observations that this number of non-thermal targets is present within the region). This would require observing about 20 primary fields of view distributed across the region, and ideally the capability of targeting simultaneously 10 to 20 fields within each primary field. With the current SKA1-MID baseline design of four VLBI beams per primary beam, and restricting ourselves to one calibrator and three targets per primary beam, we would need to observe each primary field at least 3 times. Assuming further that we focus on fields where calibrators brighter than 500 μJy exist, we would need 4 (epochs) × 20 (primary fields) × 3 passes per field × 1 hour (per field) = 240 hours. Including a 20% overhead brings the total required time for this project to 300 hours. If the capability of 10 to 20 VLBI beams was implemented in phase 1 this project would take only 100 hrs.

4.2 SKA2

If the observations with SKA1-MID are successful, we would move on to a more ambitious project utilizing the full SKA2. Taking advantage of the order of magnitude improvement in sensitivity, we would be able to carry out similar tomographic observations up to 2-3 kpc, i.e. the distance of the nearest spiral arm segments. For time estimate purposes, we will consider the mapping of a representative portion of a spiral arm segments of length 250 pc, and height 60 pc located at about 2.5 kpc of the Earth. This corresponds to a solid angle of 32,900 square arcminutes, or 180 SKA fields of view. We would, of course, only image the portions of the fields that contain young stellar objects or calibrators, thereby alleviating the computational requirements of the experiments. Assuming again 4 epochs, one hour per epoch, and 20% overheads, we obtain a total of 1,000 hours to obtain a complete tomographic mapping of a nearby spiral arm segment.

5. Conclusions and specific requirements

Thanks to its extraordinary collecting area, the SKA will be the premier instrument for radio frequency astrometry. In this contribution, we make the case for using that capability to obtain tomographic mapping of star-forming regions and spiral arm segments within several kpc of the Earth. This would represent a unique contribution to galactic dynamics, and would have important implications for spiral structure theories.

The general requirements to reach the necessary astrometric accuracy are given in detail in Green et al. (2015) and Paragi (2015). Here we emphasize that to carry out the tomographic observations presented here, at least a few tens of targets would have to be observed in a single primary beam of the SKA1-MID antennas. This would include both young stellar sources (targets)

and background quasars (calibrators). Without this capability, the time needed to carry out the observations would become prohibitive.

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