Star Formation at High Angular Resolution

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The role of the SKA in high resolution observations of the formation of low and high mass stars in the Galaxy is examined. The large collecting area will have a large impact on dynamical studies at high resolution using spectral lines. The SKA will allow dramatic progress in the investigation of the ionised, atomic and molecular phases over a range of evolutionary stages. Attention is focused here on the potential of radio recombination lines, the H I 21 cm line and molecular Zeeman measurements. This combination will unveil the physical processes that drive jets and winds from young stars. Other important areas such as pre-biotic molecules, disc ablation in OB clusters and massive star formation in nearby galaxies are also briefly discussed.

1. Introduction

The giant leap in sensitivity provided by the SKA and its large and flexible range of capabilities will provide ways to answer key problems in star formation in the Galaxy and in nearby galaxies. The impact of the SKA on studies of the ionised, atomic and molecular phases are considered below. Ionised gas occurs in jets, stellar winds, shocked regions and H II regions and is the most obvious aspect where the SKA will bring vast new insight. The very high continuum sensitivity of the SKA will enable new studies of weak emission regions. However, in a galactic context the order of magnitude increase in sensitivity that will become available with the EVLA and e-MERLIN will have already delivered continuum maps of large samples of jets and winds from young stars. These will cover a range of masses, ages, inclination angles, etc., sufficient to permit firm conclusions to be drawn vis-à-vis the geometry of the mass-loss. The major unique capability that the SKA will bring is the ability to trace the dynamics of these outflows via recombination lines at high resolution.

The principal driver for the SKA is the ability to detect H I and this will bear considerable fruit in star formation studies. This component has hardly been explored at all so far due to lack of sensitivity at the required resolution. A key question here is whether the high spatial resolution will be able to cut through the enormous amount of line-of-sight H I that be-devils galactic observations, especially towards star forming regions. Most molecular studies will be provided by ALMA and the SKA contribution here will be in terms of mapping the magnetic fields that lie at the heart of the star formation process.

2. Ionised Gas

Outflows are likely to play a dominant role in angular momentum loss and in setting the final mass of a star as the infalling material is cleared away (e.g. Shu 2003). A wind interacts with the larger scale cloud increasing the turbulence. The effects of the more massive stars can both trigger further star formation (Elmegreen & Lada 1977) and eventually disperse the cloud (Franco et al. 1994). Observations of the kinematics of these outflows at sufficient resolution is the key to understanding the physics driving them. It is also important to catch these outflows at the onset since this is where they will have most impact on the formation process itself. This necessitates the study of the youngest and most embedded objects and hence the radio regime is the only one that can deliver extinction-free views of this process. There are good reasons for believing that the physics behind the formation of low and high mass stars is different.

2.1. Low-mass star formation

For low-mass stars the outflow is usually highly collimated in the form of a jet (Eislöffel et al.

2000). The general consensus is that these jets are driven by magneto-hydrodynamic forces, but the actual controlling processes are still far from clear. In particular, the geometry of the magnetic field is unknown and even whether it is the field originating in the star, accretion disc or the interaction of the two that is important (Breitmoser & Camenzind 2002, Ouyed & Pudritz 1997, Shu & Shang 1997). The innermost regions of the disc are thought to be disrupted by strong stellar magnetic fields with in-fall then occurring along field lines. This has implications for the planetary formation process.

Since the magnetic field itself is difficult to observe in detail, the best way to distinguish between these competing models is to observe the velocity field in the outflow where it is launched and collimated. Radio recombination lines provide the only means to do this for the highly embedded young objects not seen directly even in the mid- and near-IR - the so-called Class 0 objects (André et al. 1993). These are the ones with high in-fall and outflow rates where much of the key star formation physics is occurring. Currently the VLA can detect and resolve the continuum emission of only the bases of these dense jets (e.g. Figure 1a and Reipurth et al. 1999).

Optical line observations are just beginning to resolve the velocity structure in less embedded objects. Bacciotti et al. (2002) have used STIS observations of the jet in DG Tau to reveal that a significant amount of angular momentum is indeed removed by the jet. The angular resolution of the SKA of 7 mas at 20 GHz corresponds to 1 AU at the distance of the nearest low-mass young stars in Taurus. This is just the scale where the models predict significant acceleration and collimation to occur. At these scales the jet is usually obscured in the optical and even the near-IR. Imaging interferometers operating in these wavebands are the only other facility that will be able to probe milli-arcsecond scales in the mean time. A comparison of detailed studies of the velocity structure of the ionised jets from the SKA with that seen in the molecular discs from ALMA observations will allow a comprehensive theory of accretion, outflow and angular momentum transport to be realised.

The more evolved T Tauri stars often exhibit variable non-thermal radio emission which is sometimes associated with X-ray emission as well (e.g. Feigelson et al. 1998). This is thought to arise via gyro-synchrotron emission linked to the magnetic flaring activity in the star/disc magnetic field interaction. Strong magnetic events in the solar nebula are needed to explain some features seen in meteorites. The wide-field/multi-beaming capability of the SKA would allow monitoring of a large number of targets to study the timescales and energetics of this phenomenon. The high resolution of the SKA may be able to localise the activity to the star or disc and test predictions in this context of the X-wind model (Shu et al. 2001). With most star formation occurring in clusters there will be a large multiplexing possible with many of the star formation studies (e.g. Rodríguez et al. 1999). The one degree field of view of the SKA is easily sufficient for this.

A large proportion of low-mass stars form in clusters, which have luminous, young OB stars at their centres (Carpenter et al. 2000). The UV radiation and winds from the early-type stars are sufficiently strong to photo-evaporate and destroy the circumstellar discs around the lower mass stars. This could have a significant effect on the fraction of stars that go on to form planetary systems. So far this ablation process has only been seen in the nearest massive star-forming region in Orion 0.5 kpc away (O'Dell & Wen 1994). The ionised gas flowing off the discs is seen in the radio continuum at the level of a few mJy (Garay, Moran & Reid 1987) which is spatially resolved by MERLIN (Graham et al. 2002). This disc destruction phase is likely to be short-lived and so a large sample of evolved H II regions, i.e. up to 10 times further away, will need to be searched for this phenomenon to gauge its importance. This is likely to require the sensitivity and resolution of the SKA.

2.2. High-mass star formation

Young high mass stars themselves also emit thermally at radio wavelengths even before they begin to ionise the surrounding ISM to form ultra-compact H II regions. A few of these have been resolved to reveal highly collimated radio jets which are similar to their low-mass counterparts (Martí et al. 1998; Rodríguez et al. 1994). However, the very extended optical and near-IR jets seen in low-mass star-forming regions are certainly not the norm (Poetzel et al. 1992; Davis et al. 1998). Other high mass young stellar objects have been shown to drive an equatorial outflow via high resolution radio mapping (Figure 3 and Hoare 2002). This has been interpreted as material being driven off the surface of an accretion disc by the radiation pressure of the luminous young star (Drew et al. 1998). When jets are seen in high-mass objects then it implies that a magneto-hydrodynamic mechanism is at work as for low-mass objects, although purely hydrodynamic collimation mechanisms have been investigated (Mellema & Frank 1997). At present it is unclear whether the dichotomy between jets and equatorial winds, and by implication magnetic and radiative driving mechanisms, is a function of evolutionary stage, mass, or initial conditions.

Radio continuum mapping of large samples with e-MERLIN and EVLA will reveal which of these geometries is common and go some way to answering these questions. Recombination line mapping of the dynamics with the SKA will test the disc ablation scenario and determine whether this is important in setting the final mass and hence the upper IMF. In the case of high mass jets the velocity structure should distinguish between MHD and hydrodynamic collimation; the former likely to impart more rotation into the jet.

The extreme continuum sensitivity of the SKA should allow the thermal wind emission from massive young stellar objects to be detected in near-by metal-poor galaxies like the Magallenic Clouds. Typical fluxes of nearby ($\sim$1 kpc) examples are about 1 mJy, which corresponds to 300 nJy at 55 kpc. This will allow an investigation of the mass-loss rate as a function of metallicity for a given luminosity. In particular, if the line-driven equatorial wind scenario is confirmed then the mass-loss will scale with metallicity as is being demonstrated for main sequence OB stars (Crowther et al. 2002). Furthermore if the ionised winds also play a role in setting the final mass of the star this could then lead to the first concrete proof of a physical mechanism whereby lower metallicity environments lead to more massive stars.

A few very dense and compact H II regions with rising spectral indices have been found to have components in their radio recombination line profiles broader than expected (Jaffe & Martín-Pintado 1999; Sewilo et al. 2004; De Pree et al. 2004). The large widths (60-100 km s^{-1}) are not due to pressure broadening and must reflect the dynamics. The widths are reminiscent of the even broader near-IR recombination line profiles from the ionised winds from the massive young stellar objects discussed above (e.g. Bunn et al. 1995). However, their radio continuum brightnesses are much higher than these pure ionised wind sources.

Several of the very compact objects exhibit bipolar morphologies like one of the original sources in this class NGC 7538 IRS 1 (Gaume et al. 1995). Photo-evaporating discs have therefore been suggested as a possible explanation, but like compact H II regions themselves these only give rise to thermal gas motions and would therefore struggle to explain such widths. Photo-evaporation also ignores the effect of radiation pressure that explains the equatorial winds seen in some massive YSOs. Perhaps these broad recombination objects represent a transition phase from a massive YSO wind to ultra-compact H II region. A fast radiatively driven wind could mass-load sufficiently to produce the bright radio emission at intermediate velocities. Gaume et al. (1995) invoke this kind of picture for NGC 7538 IRS 1. Alternatively an extreme champagne-type flow could occur rather like a small-scale version of the 'blow-out' proposed for one of the larger scale broad recombination line objects S106 (Dyson 1983). As the Lyman continuum radiation from the central star turns on ionised gas would expand rapidly down the bipolar cavity previously evacuated by the predominately molecular outflow.

It is the classical H II regions that have traditionally been the subject of radio investigations of massive star formation. Most of the remaining questions concerning galactic H II regions such as their dynamics and evolution are likely to have been solved before the SKA begins operation, even for the ultra-compact ones (e.g. Lumsden

& Hoare 1999). The new field opened up by the SKA will be to carry out the kind of studies currently done on galactic H II regions in nearby spiral and irregular galaxies. Relatively face-on spirals such as M 33 present an excellent environment in which to examine the global aspects of massive star formation as traced through their H II region populations. The SKA resolution of 17 mas at 5 GHz corresponds to nearly 0.05 pc in M 33. This is the realm of ultra-compact H II regions, which are commonly still deeply embedded in their parent molecular cloud and thus not accessible to optical or even near-IR studies. Being young, they also have the most relevance to the conditions in which the OB stars were born. Typical fluxes in M 33 for such objects are tens of nJy even if powered by a B2V star. Hence, we can probe the whole upper IMF. Currently, we are just skimming the top of the IMF with the VLA in terms of the compact H II region population in M 33 (Figure 2 and Pattison & Hoare, in prep.).

For the brighter objects it should be possible to again use the collecting area of the SKA to detect their recombination lines. This is doable now for galactic H II regions at high resolution using the VLA (e.g. Wood & Churchwell 1991). The power of such velocity studies with the SKA will be in combination with CO studies from ALMA and H I with the SKA to build up a 3D picture of where massive stars are forming. This can then be related to possible triggers of gravitational collapse such as the spiral density wave, clusters of more evolved OB stars and supernova remnants. Such a dataset can discriminate between density wave and self-propagating models of spiral structure. The question of what triggers massive star formation is much easier to answer in nearby spirals than in our own galaxy due to the problems of everything being along the same line-of-sight in the galactic plane.

2.3. Recombination line mapping

The big step forward from studies of the ionised gas in galactic star formation with the SKA will come from probing dynamics at the highest resolution. For stellar wind sources a crude estimate of the strength of the recombination lines can be made from the ratio of the line brightness temperatures from the optically thin part of the wind to the continuum brightness temperature. It has been observed that even when a source is optically thick in the continuum, recombination lines at the same frequency are still easily detectable from the surrounding diffuse envelope (Sewilo et al. 2004). Altenhoff et al. (1981) show for a constant velocity wind that typical line-to-continuum brightness temperature ratios are of order 0.1. The continuum brightness temperatures seen at current resolutions in stellar jets and winds are in the range of 10^{2-4} K (Rodriguez 1999; Hoare et al. 1994; Hoare & Muxlow 1996). At higher resolution we can expect higher continuum brightness temperatures in the regions of interest and so the line brightness temperatures will be about 100 K.

This is currently the sensitivity of the VLA in a 10 km s^{-1} channel after a 12 hr integration with $0.1''$ resolution at 20 GHz. Gaume et al. (1995) used this setup to resolve the very strong, broad recombination lines from the young high-mass source NGC 7538 IRS 1. Hence, the SKA, with two orders of magnitude better line sensitivity, can map these sources at 10 times better resolution and hence probe the dynamics at interesting scales.

Many aspects of recombination line physics (see Gordon & Sorochenko 2002) drive the SKA requirements to the highest frequencies apart from the need for the highest spatial resolution. Firstly the lines themselves get stronger with increasing frequency. The line-to-continuum ratio of the H66α line at 22.4 GHz is at least an order of magnitude higher than that for H166α at 1.4 GHz. Another severe problem for lower frequency lines is that of pressure broadening. The ratio of pressure broadening Δv^l to Doppler broadening Δv^D is given by

$$\frac{\Delta v^l}{\Delta v^D} = 0.14 \left(\frac{n}{100}\right)^{7.4} \left(\frac{n_e}{10^4}\right) \qquad (1)$$

where n is the principal quantum number and n_e is the electron density (Keto et al. 1995; De Pree et al. 2004). Hence, for the highest frequency line likely to be observed by the SKA (H66α) only densities up to about 10^6 cm^{-3} can be observed before pressure broadening begins to dominate.

When it does dominate the lines will become much more difficult to detect and less useful as probes of the dynamics. Martin (1996) deduced that the electron density at 1 AU from the star for typical T Tauri star jets is at least 10^7 cm^{-3} and could be much higher. However, in any kind of wind the density falls off very rapidly, usually as r^{-2}, and so parts of the wind will still produce narrow components to the line profile that are good tracers of the kinematics. The sensitivity to density via the pressure broadening at the transition between thermal and pressure broadening, of course also allows an accurate measure of density which will be another valuable probe.

A possible disadvantage of higher frequency recombination lines is their susceptibility to stimulated emission and maser emission. This is seen in the highest frequency recombination lines in the millimetre regime in the wind of the enigmatic object MWC349A, whose nature is not fully understood (Martín-Pintado et al. 1993). Again this would make interpretation of the velocity and density structure more difficult. Non-LTE effects are also common in radio recombination lines. Martín-Pintado et al. (1993) and Jaffe & Martín-Pintado (1999) attribute the broad flat-topped cm lines to non-LTE effects.

With the large bandwidth and a flexible correlator it will also be possible to observe about 10 recombination lines simultaneously enabling constraints on the velocity and density structure through one observation as well as increasing the significance of line detections overall. Multiple lines also help disentangle the effects of stimulated emission and departures from LTE. Detailed modelling of the strengths and profiles of radio recombination lines needs to be done for stellar jets and winds to fully appreciate what the SKA will and will not be able to do in this field.

3. Atomic Gas

The very high sensitivity of the SKA to atomic hydrogen via the 21 cm line will also provide unique new insights into the star formation process. Again this is most likely to come in the realm of outflow studies, not because there is little atomic gas involved, but rather because there is too much. The star forming clouds will have significant atomic layers both near the young stars as they dissociate the dominant molecular component and around the edges of the complex. This together with the abundance of H I along the line of sight to most star forming regions in the galaxy presents a vast confusion problem at velocities close to the systemic velocities of forming stars. The high spatial resolution of the SKA will certainly resolve out much of the confusing gas, but it is most likely to be the spatial resolution combined with high velocity signatures that will give clear new insights into the physics of star formation. As is clear from Figure 1 only a small fraction of the mass-loss in stellar jets from low-mass young stars is ionised. Most of the mass of these jets is therefore likely to be in atomic form, although some may also be molecular. Shocked molecular hydrogen emission associated with the jet has been seen in a few cases (e.g. McCaughrean et al. 1994).

Atomic hydrogen that can be directly associated with outflows from young stars has only been seen in a couple of cases so far. Lizano et al. (1988) found H I emission wings up to 170 km s^{-1} towards the exciting source of HH 7-11 using Arecibo. The derived mass-loss rate of 3×10^{-6} M$_\odot$yr^{-1} is sufficient to drive the CO flow from this object. Rodríguez et al. (1990) used the VLA to resolve the intermediate velocity H I into a bipolar flow similar to the known CO flow. Extended intermediate velocity bipolar H I emission has also been detected at about arcminute resolution from L1551 by Giovanardi et al. (2000). Higher velocities still were seen in Arecibo observations of L1551 by Giovanardi et al. (1992). Giovanardi et al. (2000) modelled the L1551 emission as a bi-conical interaction zone between a high speed wind and the walls of the bipolar molecular flow.

Current facilities are unable to pick up any H I emission directly from the highly collimated jets, but this will be a key aim of SKA studies. The resolution of 100 mas at 1.4 GHz is unlikely to be sufficient to probe right into the acceleration and collimation zones as the high frequency recombination line studies will. However, H I will reveal the velocity structure in the bulk of the mass of the flow and so should yield further important constraints on the mass-loss mechanism. If the density in the jet is about 10^6 cm^{-3} and it is 100 AU in diameter then the H I column density is around 10^{21} cm^{-2}. For emission spread across 10 km s^{-1} this corresponds to an antenna temperature of 100 K which is within the capabilities of the SKA operating at its highest angular resolution. These kind of jet parameters also give significant H I optical depth against the bright continuum emission from the ionised portion of the jet. The well-defined geometry of absorption will yield additional constraints on jet models.

The SKA H I resolution of 15 AU at Taurus would be able to resolve the surface atomic layer of the accretion discs themselves if the ambient and line-of-sight material can be sufficiently resolved out. This will allow the dynamics of this interface zone between the Keplerian outer disc (studied with ALMA) and the radiation and flows from the inner disc region to be studied. It is here where the clearing of the infalling envelope and launching of any wind-angled wind may take place.

If suitable narrow velocity components can be found in the dense ambient atomic gas then Zeeman measurements may be possible. These could be in emission or in absorption against the weak continuum, analogous to what is done against strong H II region continua at present (Crutcher 1999). This would enable the magnetic field strength and line-of-sight geometry to be studied at high resolution. Continuous spatial measurements would have much greater diagnostic power than the sparse and possibly special locations currently made using OH masers.

4. Molecular Gas

By the time the SKA begins operations ALMA will have revolutionised our view of the molecular gas at high resolution in star forming regions. The detailed molecular observations will be the setting in which the ionised and atomic dynamical studies by the SKA described above will take place. However, the SKA will also make important contributions to our understanding of the molecular environment through high resolution magnetic field measurements. With nearly every aspect of star formation, certainly for low-mass stars, thought to be controlled by magnetic processes the importance of this cannot be understated.

Although progress will have been made in the use of millimetre-wave transitions of molecules such as CN for Zeeman splitting measurements using ALMA (Crutcher et al. 1999) there are advantages to using cm-band transitions. The large Zeeman splitting of molecules such as CCS holds great promise for detecting weak fields or mapping strong ones at high resolution (Levin et al. 2001). The cm transitions of heavy molecules also have the advantage of reduced thermal line widths and being able to penetrate deep into dense cores without the dust becoming optically thick. The combination of measurements from emission and absorption against the continuum from these and the traditional Zeeman transitions of H I and OH will help reveal the geometry of the magnetic field. The velocity information from either the thermal Zeeman lines or maser measurements, which will be much more numerous than at present, will enable a three-dimensional picture of the magnetic field strength to be built up. Polarisation maps from ALMA will also help pin down the geometry. This information is another vital part of testing the models for mass-loss and angular momentum transport in young disc/outflow systems.

The extreme sensitivity of the SKA will also allow a veritable pin-cushion of extragalactic sources to be seen through dense cores before and after the onset of collapse. Absorption magnetic field measurements across the cores will be key to understanding the role of magnetic support and ambipolar diffusion in these early stages of star formation.

One final area where the SKA will make a great impact is in the detection of heavy molecules and pre-biotic molecules in particular. As ever more complex molecules form in the densest parts of the proto-planetary discs their main transitions inevitably move from mm to cm wavelengths. Models of proto-planetary discs are now being developed which provide a two-dimensional axisymmetric solution of the coupled physical and astro-chemical problem to predict molecular distributions in the inner 10 AU of the disk (Ilgner et al. 2004). The upper layers of the discs where much of the line formation takes place require a full treatment of the ionisation and dissociation fronts. Chemical models of complex organic molecule synthesis will then predict the concentrations and distributions of biologically relevant species such as glycine, adenine and other DNA bases. Many of these species have low-lying rotational transitions at frequencies of less than 20 GHz. Hence, the SKA will provide the ideal capability to map out the development of pre-biotic molecules during the later stages of the star formation process.

5. Conclusions

The SKA will make valuable contributions to our understanding of star formation through its ability to probe the dynamics of ionised and atomic gas at high resolution. Coupled with the SKA's pre-eminence in magnetic field mapping it will enable the driving mechanism of collimated and equatorial mass-loss from low and high mass young stellar objects to be firmly established. Key pieces in the planet formation puzzle will be put in place through studies of the disruption of the disc by stellar magnetic fields and photo-evaporation by near-by OB stars. Galactic H II region studies will be transfered into nearby galaxies where the combination of SKA and ALMA will allow the global and local triggering of high-mass star formation to be established. The possibility of directly measuring the metallicity dependence of mass-loss from young stars will have significant implications for our understanding of star formation at high redshift.

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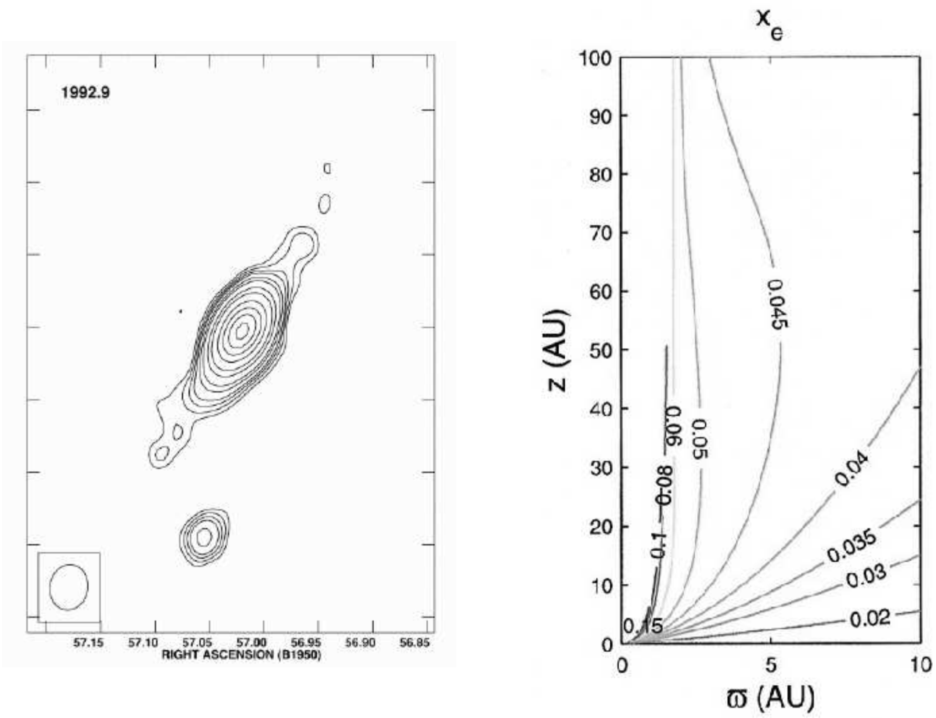

Figure 1. a) 6cm VLA continuum map of the radio jet VLA 1 that powers the HH 1 region at 0.5″ resolution. The other unresolved source is VLA 2. The peak continuum brightness temperature is 100 K. From Rodríguez et al. (2000). b) Predicted ionisation fraction structure for an X-wind model for YSO jets. Note the physical scale in AU assuming a distance of 150 pc appropriate for the nearest low-mass star-forming regions. From Shang et al. (2002).

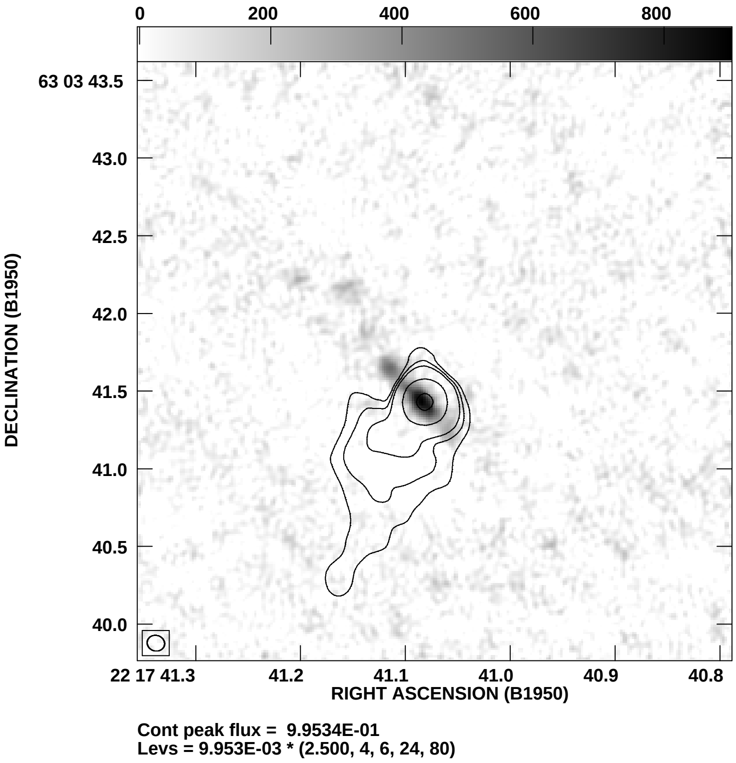

Figure 2. MERLIN 5 GHz image of the equatorial wind from the massive young stellar object S140 IRS 1. Overlaid are contours of a high resolution near-IR image showing the monopolar reflection nebula arising from light scattered off the walls of the lobe of the bipolar molecular outflow directed towards us. The SKA will be able to probe the dynamics of these important mass-loss processes at resolutions at least as high as this. From Hoare (2002).

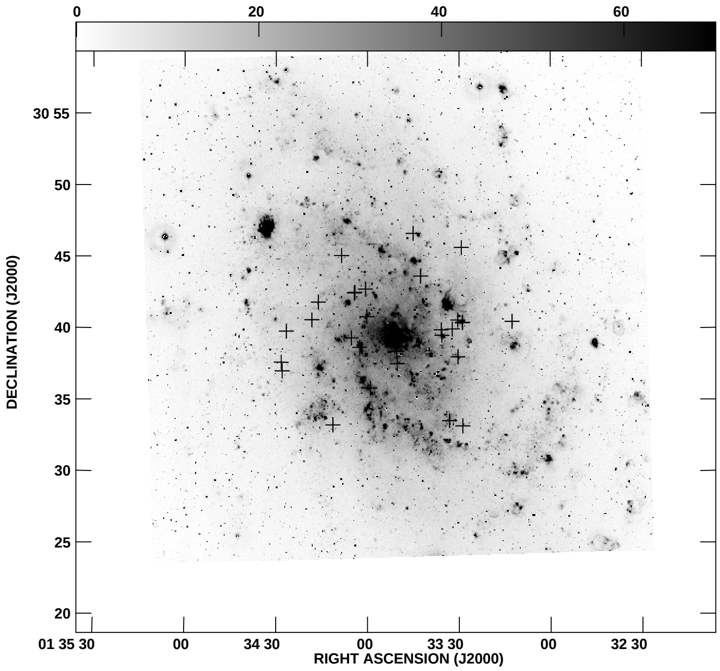

Figure 3. Crosses mark the locations of young, dense H II regions found in a 2 hour 5 GHz VLA A configuration observation overlaid on an Hα image of the nearest relatively face-on spiral M 33. From Pattison & Hoare, in prep.