e-MERLIN Legacy Proposal
"Morphology and Time Evolution of Thermal Jets Associated with Low Mass Young Stars"

Abstract

We plan to take advantage of the unprecedented combination of sensitivity (1 μJy) and angular resolution (50 mas) of e-MERLIN at 5-7 GHz to image the free-free emission from a list of selected jets associated with low-mass protostars. The main goal of these observations will be to obtain unique information on their structure to test specific morphological predictions of jet models and to compare with matching-beam 43 GHz observations (50 mas) made with the EVLA that are expected to trace the dust from the disk. This will be the first time that the comparison between the dust and free-free emissions will be feasible at these high angular resolutions, leading to an improved understanding of the jet-disk relation and of the physics that characterizes low-mass star formation.

Participants

This project will count with participants from seven institutions: the University of California at San Diego, USA (Frank Shu; shufrnk5@netscape.net), the Centro de Radioastronomia y Astrofisica of UNAM in Mexico (Susana Lizano; s.lizano@astrosmo.unam.mx, Luis F. Rodriguez; l.rodriguez@astrosmo.unam.mx), the University of Leeds, UK (Melvin Hoare; mgh@ast.leeds.ac.uk), the Cavendish Laboratory, UK (John Richer; jsr@mrao.cam.ac.uk), the Dublin Institute for Advanced Studies, Ireland (Tom Ray; tr@cp.dias.ie), the Thüringer Landessternwarte Tautenburg, Germany (Jochen Eislöffel: jochen@tls-tautenburg.de), and the Institute of Astronomy and Astrophysics of the Academia Sinica in Taiwan (Jeremy Lim; jlim@asiaa.sinica.edu.tw, Paul Ho; pho@asiaa.sinica.edu.tw, Hsien Shang; shang@asiaa.sinica.edu.tw, Mike Cai; studbud@asiaa.sinica.edu.tw).

The team is a combination of observers and theoreticians that will extract the maximum information from the e-MERLIN data.

Scientific Justification

Introduction: The early stages of star formation take place in heavily obscured regions of space: only radio, mm, and far-infrared wavelengths can be used to penetrate the dust envelopes surrounding the forming star. Furthermore, many of the relevant processes such as disk formation and jet collimation take place on scales smaller than 100 AU (about 1" at the distance of the closest star-forming regions). These considerations lead to the conclusion that long wavelengths and high angular resolution are needed to understand the assembly of a new star. Far-infrared astronomy has not reached the required angular resolutions and we are left with radio and mm wavelengths to study these key, early stages in star formation.

Comparison with mm observations: Indeed, several groups have used radio continuum (cm) observations made with interferometers to produce a list of significant results over the years. The most significant of these results are:

1) The jets associated with young low-mass protostars are systematically detected as thermal (free-free) sources of modest flux density, of order 1 mJy (Rodríguez & Reipurth 1996).

2) When resolved, these thermal radio sources show an elongation nearly parallel to indicators of the outflow at larger scales (i. e. Herbig-Haro objects and molecular outflows) and are thus believed to trace the "base" of the outflow phenomenon (e. g. Reipurth et al. 1999). These results have also provided upper limits to the minor axis of the jet and have made possible to establish that the collimation of the jets takes place on scales of 100 AU or less. The e-MERLIN will improve these upper limits by an order of magnitude and may possibly measure the actual, yet unknown scale of the collimation (although it is also possible that the scale is still below e-MERLIN's angular resolution).

3) In a few sources, it has been possible to follow the motion of individual ejections and to measure the velocity of these ejections in the plane of the sky (e. g. Rodríguez et al. 2000). These measurements are very important because they provide velocity information very close to the origin of the jet.

4) Also in a few sources, it has been possible to obtain high angular resolution images at shorter wavelengths (mm) that in some cases trace the emission from dust in circumstellar structures, possibly disks (e. g. Lim & Takakuwa 2006). The comparison between cm and mm observations has been difficult and relatively inconclusive since, while the EVLA at 7 mm can

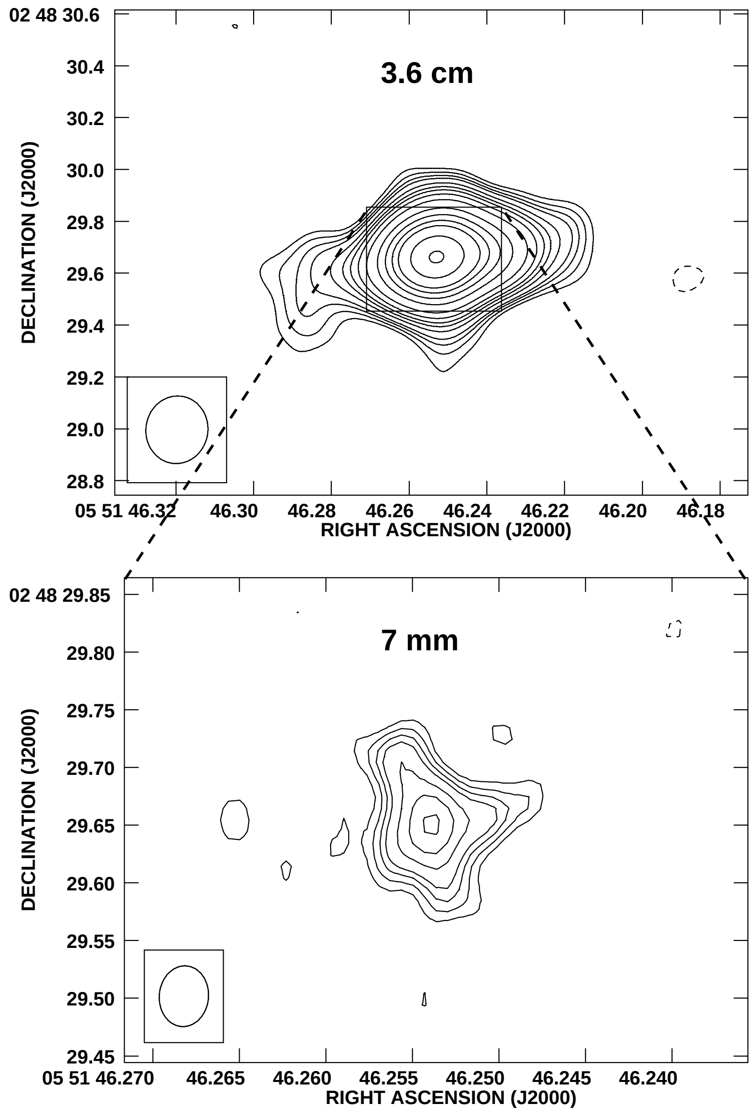

Figure 1: Top: 3.6 cm VLA image of the core of the double outflow HH 111 region, made with an angular resolution of 0."25. Bottom: 7 mm VLA image of the core of double outflow the HH 111 region, made with an angular resolution of 0."05. The very different angular resolutions difficult a reliable comparison between the 3.6 cm image (tracing the ionized gas) and the 7 mm image (tracing the dust). From Rodríguez et al. (2008, in preparation).

reach an angular resolution of 50 mas at 7 mm, there is no instrument at present that can reach this angular resolution with the required sensitivity. An example of this problem is shown in Figure 1, where VLA 3.6 cm and 7 mm images of the exciting source(s) of the HH 111 double outflow region are compared. The angular resolutions are different by a factor of five, making a comparison very difficult. e-MERLIN will be the first instrument capable of producing cm images with the required angular resolution and sensitivity and will allow for reliable comparisons and the study for the first time of a physical scale yet unexplored at cm wavelengths.

Comparison with theoretical predictions of the X wind model: Our observations will provide crucial new information on the nature of outflows from low-mass young stars. We discuss in some detail the X-wind case below, emphasizing that any specific predictions of the models will have to compare with the e-MERLIN observations. The interaction of accretion disks with the magnetospheres of young stars is expected to produce X-winds and funnel flows (Cai et al. 2008). The unprecedented combination of angular resolution and sensitivity of e-MERLIN will allow to obtain unique information on the structure of the jets and to compare with specific morphological predictions of the X-wind model, in particular a deficit of emission in the core of the jet, as compared to naive extrapolations, produced by the existence of a "hollow cone" created by longitudinal field lines that are "dead" to magnetohydrodynamical flow. The existence of these field lines is critical to the stabilization of the jet to "sausaging" and "wiggling" instabilities that would otherwise arise from the "pinch" of collimating hoop stresses. The models of Shang et al. (2008, in preparation) predict that under some assumptions the width of the cone could be several AU and comparable with the e-MERLIN angular resolution for nearby low-mass star-forming regions. Even when the dominant emission mechanism that we will detect (free-free emission) does not contain direct information on the magnetic fields involved (as do other mechanisms like synchrotron or gyrosynchtrotron), the appearance of the model depends on the magnetic field, among other parameters (Shu et al. 1994).

It should also be pointed out that the direct measurement of the dimensions of the jet at its base may help favor either a disk origin (Königl & Pudritz 2000), where the base of the jet should be eventually resolved angularly, or a central star origin (Shu et al. 2000), where the base of the jet will be very small and unresolved.

Possible magnetic field information: We noted in the previous section that we expect to detect mostly free-free emission. There is, however, the tantalizing possibility of detecting non thermal emission associated with the jets and estimating the magnetic field strength. It is important to emphasize that magnetic fields are the only important unknown parameter in these jets and that it is a crucial element in the phenomena: all jet acceleration and collimation models involve centrifugal ejection of jet material along magnetic field lines followed by subsequent collimation through magnetic hoop stresses. It is thought that the same basic MHD mechanism is responsible for the launching of jets in objects as diverse as brown dwarfs, forming stars, planetary nebulae, micro-quasars and active galactic nuclei (AGN) and information on the magnetic fields present is of enormous value. A small number of jets have a non thermal spectrum (Shirley et al. 2007; Wilner et al. 1999; Ray et al. 1997) and the improved sensitivity of e-MERLIN opens the possibility of studying in a systematic way this type of emission.

Time variability: A key part of the project will be to obtain information on the time variability of these jets by doing a second epoch of observations about three months after the first (to address "rapid" variability) and then three years after (to address slower time changes). This time variability is believed to be associated with major ejecta events, although the lack of sensitivity up to now has not allowed to test this. After the second epoch, we expect to publish a first major paper focused on morphology and possible rapid variability. The third and final epoch will be used to study proper motions and long term variability. This evolutionary study will allow us to detect and follow ejecta events, as have been observed on jets associated with higher mass protostars, to derive the velocity in the plane of the sky and to compare with the characteristics of larger, older ejecta traced by molecular outflows. It can be argued that the variability alone can be addressed with intruments of lower angular resolution, like the EVLA. However, most of the jet structure is unresolved with the EVLA and only the bulk time variability can be addressed. With e-MERLIN we will be able for the first time to study simultaneously both time and morphological changes in the jet, that will enable us to understand better the unknown nature of the variability mechanism. With the Lovell telescope we will achieve in each epoch a surface brightness sensitivity of $\sim$80 K, that will allow us to image the outer, optically-thin zones of the jets.

Proper motions and other sources in the field: We will also obtain very accurate positions of the jet and of the other sources in the field at the different epochs that will allow the determination of systemic proper motions or of anomalous proper motions that may reveal strong gravitational interactions in the recent past (as observed in the Orion BN/KL region; Gómez et al. 2008). We expect to be able to distinguish between morphological

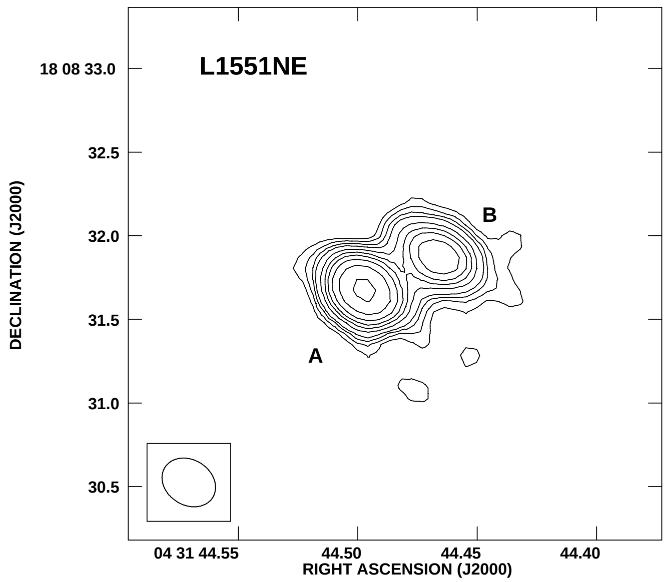

Figure 2: 3.6 cm VLA image of the double source L1551 NE. The components appear unresolved in the image but e-MERLIN will improve the angular resolution by a factor of 5, allowing a better understanding of their nature. Image from Reipurth et al. (2002).

changes and proper motions since the latter will produce a systematic shift in position with time. The observational determination of this systematic shift is also part of the motivation for asking for three epochs. Finally, the data of the different epochs will also be concatenated to obtain a supersensitive image of the regions (an rms of order 1 μJy or better) that may reveal the presence of a population of weak, persistent radio sources such as that revealed in deep radio continuum studies of a few selected regions (e. g. HH 124; Reipurth et al. 2002). Stellar multiplicity seems to be the rule, even in scales as small as a few arcsec and the e-MERLIN results will add considerably to the understanding of this phenomenon. Many multiple systems observed with the VLA show unresolved components (see Fig. 2) and it has not been possible to discuss their morphology. This will change for the better with e-MERLIN It is also possible that some of these field sources turn out to be gyrosynchtrotron emitters, whose geometric parallax can be determined with future VLBI observations to obtain very precise distances to the star forming region, as already achieved in a handful of sources (i. e. Loinard et al. 2007). The data will be calibrated for full polarization to help in the analysis of possible non thermal sources.

Sources selected: We will image 12 nearby (distance less than 500 pc), low luminosity thermal jets using a total of 10 hours per source per epoch (three epochs). These sources have been selected because they are among the brightest known in low-mass, heavily embedded protostars and because we have a good grasp of their characteristics at the large ($\geq 1''$) scales. This adds to a total of 360 hours for the whole program. With the 3-7$'$ field of view of e-MERLIN (with and without Lovell) we will also be able to study other serendipitous sources in the region. The sources selected are HH 7-11, L1551, L723, L1448, NGC 2264, HH 111, L1527, L1251, HH26IR, L1681B, Serpens, and HH 1-2. Their positions and 6 cm flux densities (measured directly or estimated from their 3.6 cm flux density assuming a power law dependence of $\nu^{0.6}$ for the flux density) are given in Table 1.

With the results of this legacy proposal we will also be able to establish, on the basis of the 5-7 GHz intensity and morphology and the presence of water-vapor masers, if additional time should be requested to image a few selected sources at 22 GHz doing cross-calibration from the masers to the continuum, to take advantage of the full e-MERLIN angular resolution. For the maser observations we will not benefit greatly of the e-MERLIN sensitivity but this is not very important since they will be observed with the main purpose of correcting phase errors in the ultrasensitive continuum data.

Contact with other coordinators: We are in close contact with Melvin Hoare, coordinator of a legacy proposal to study massive star formation. The combination of both projects will address in a powerful way the physics of stellar formation as well as what is perhaps the main issue in the field nowadays: whether or not the formation of massive stars is a scaled-up version of the formation of low-mass stars or if a different mechanism is required.

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Pipeline Processing and Data Archiving

The continuum data reduction will be made using the e-MERLIN pipeline. We also expect to participate in the solution of the challenges that will certainly appear when continuum data of such a wide bandwidth is reduced.

We do not request for deviations from the default 12 month period of data rights.

Technical Justification

We plan to use the unprecedented sensitivity of e-MERLIN in the continuum mode (1 μJy in 12 hours) to image the core (at a brightness temperature of 10^4 K) as well as the outer parts of these jets to reach the detection of brightness temperatures of order 80 K. Given the expected theoretical behavior of thermal jets (i. e. Eislöffel et al. 2000), we will be able to image over dimensions about 5 times larger than the core.

Management and Resource Plan

The e-MERLIN data adquisition and reduction as well as the data archiving will be undertaken by Ray, Hoare, Richer, and Rodríguez. Complementary 7-mm EVLA and SMA (SubMillimeter Array) observations and data reduction (including submission of proposals) will be in charge of Lim, Ho, and Rodríguez. Eislöffel will provide data at far-infrared wavelengths, in particular taking advantage of his membership in relevant LOFAR Key Science Programmes (Transients, Cosmic Magnetism). LOFAR will be able to prove emission at low radio frequencies ($\sim$100 MHz) with arcsec resolution, where any non thermal radio emission might be expected to become dominant. Finally, theoretical modeling to compare with the observations will be the duty of Shu, Lizano, Shang, and Cai.

Need for Legacy Status

In a conventional PATT proposal we can aspire to do one of the proposed sources at a time. We have selected 12 sources, a number large enough to sample in a representative way the class of low-mass protostars studied. A much larger sample would bring the required time to the range of a few thousand hours, comparable with the total time allocated for the Legacy Program in its first 2.5 years.

We are confident that this project will have a last-lasting, important impact in the fieldof star formation.

Table 1: Sources Selected

Source	α(J2000)	δ(J2000)	6-cm Flux Density (mJy)
L1448	03 25 36.49	+30 45 22.0	0.83
HH 7-11	03 29 03.73	+31 16 03.8	0.21
L1551	04 31 34.15	+18 08 04.8	0.60
L1527	04 39 53.87	+26 03 09.9	0.75
HH 1-2	05 36 22.85	-06 46 06.6	1.11
HH 26IR	05 45 57.76	-00 09 28.7	1.27
HH 111	05 51 46.25	+02 48 29.7	0.83
NGC 2264	06 41 11.05	+09 55 59.2	0.27
L1681B	16 27 26.90	-24 40 49.8	1.33
Serpens	18 29 49.79	+01 15 20.8	2.07
L723	19 17 53.67	+19 12 19.6	0.22
L1251	22 35 24.95	+75 17 11.4	0.15