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MERLIN and Global VLBI Observations of θ^1 Orionis A

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Abstract. The Trapezium Cluster within the Orion Nebula is the richest and densest young stellar cluster known in our Galaxy. Early VLA observations revealed a wealth of compact radio sources, ranging from compact thermal emission, now known to be associated with the "proplyds", to highly variable non-thermal emission from a number of young, active stars, including θ^1Ori A, one of the Trapezium stars.
MERLIN 6cm observations have recently provided the most detailed radio images yet of the ionized gas, arising from photo-evaporation of protoplanetary disks (proplyds). Further, higher resolution radio observations may shed further light on the microjets and shock interactions, which are just beginning to be resolved in these images.
The astrometry provided by the MERLIN observations show that the radio emission from θ^1Ori A is most likely associated with a companion, now clearly identified by speckle interferometry. New Global VLBI observations, using phase referencing, confirm this position and show that the emission is easily detectable on transatlantic baselines. The emission may be marginally resolved with a fitted size of 1 mas, implying a brightness temperature of 10^8 K. The question of how such emission arises in what appears to be a 4-5 $M_\odot$ pre-main-sequence star remains a puzzle. Finally, we discuss the prospects for future VLBI astrometry of this companion star, which would allow the determination of the binary orbit, and well as the most accurate trigonometric parallax of the Trapezium cluster.

1. Introduction

The Orion Nebula offers a unique opportunity to study the formation of both low and high mass stars at close hand and the Trapezium Cluster is the richest and densest young stellar known in our Galaxy. High resolution radio observations of the Orion Nebula have played an important role in studies of this region. The compact thermal radio sources, first identified using the VLA by Garay et al. (1987), were interpreted as photo-evaporating proto-stellar disks (Churchwell et al. 1987). This hypothesis has been confirmed by the spectacular HST images which resolved the optical knots seen by Laques and Vidal (1979) into the so-called 'proplyds', or proto-planetary disks (O'Dell et al. 1993, Bally et al. 2000).

VLA observations and monitoring also found a number of compact, possibly non-thermal, variable sources associated with stars in Orion. The brightest of these was associated with θ^1Ori A, one of the trapezium stars. VLA observations show high variability (3 - 90 mJy), and a flat or negative spectral index (Felli et al. 1989, 1993). The nature of the radio emission from this object remains an enigma, not least since it is now clear that the radio emission comes from a third star in this system.

2. MERLIN Observations of the Proplyds

Deep 6cm MERLIN observations of the Trapezium field have recently produced detailed radio images of the proplyds (see Figure 1). These have provided new detailed radio views of the ionized material surrounding these low mass YSO's.

The MERLIN image of LV2 (Henney et al. 2002) shows the thin cusp of the ionisation front where the photo-evaporated wind from the proto-planetary disk is ionised by the the UV flux from θ^1 Ori C, the brightest of the Trapezium stars. Like many of the other proplyds in the Trapezium cluster, LV2 has a mono-polar jet, first seen in long-slit spectra, and then in the HST images directly (eg Bally et al. 2000). The jet could not be resolved in previous VLA images, but appears to be more visible in the MERLIN image than in the optical images. Since the jet is redshifted, we are viewing it through the dusty disk material and hence the optical view of the inner jet is obscured. Future radio observations with higher resolution and sensitivity may provide valuable insights into the nature of these microjets which are now known to be common amongst the Orion proplyds.

The bright proplyd LV1 was first resolved into two sources by the 2cm VLA images and subsequently by high resolution HST (O'Dell & Wen 1994) and ground-based IR observations (Petr et al. 1998). The MERLIN 6cm image shows three distinct components. Careful registration of the radio and optical images shows that the the two outer radio components are associated with the two proplyds, while the central component is associated with an interaction zone, now seen quite clearly in the HST [OIII]5007 line images (Graham et al. 2002). As in LV2, the radio emission in this region is more prominent than the Hα emission, and from comparison with the 2cm VLA images, it would also appear to be more prominent at the longer radio wavelengths. Graham et al. (2002) describe a model

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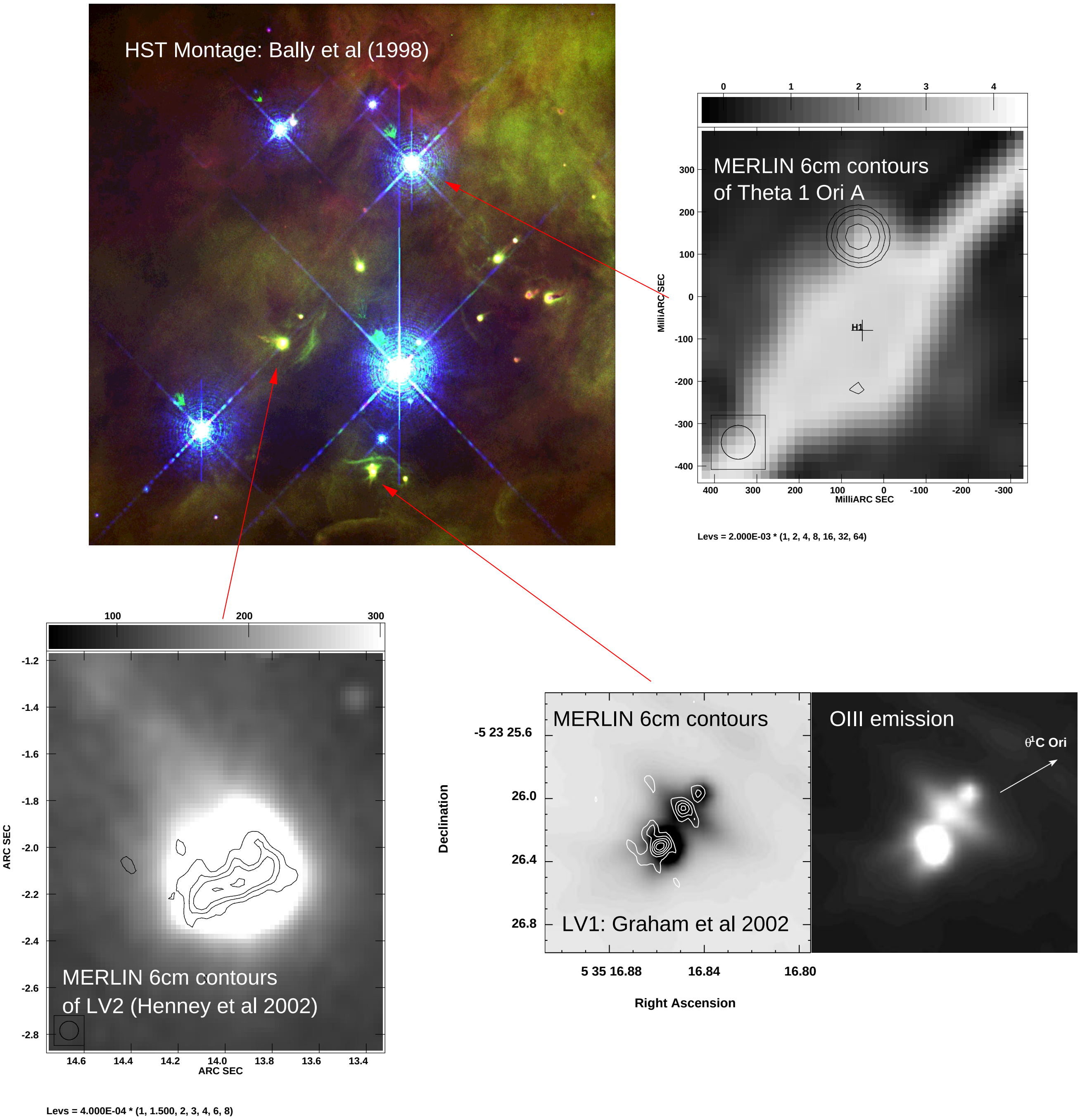

Fig. 1. An emission-line montage of the ionized gas in the Trapezium cluster from Bally et al. (1998) showing several proplyds surrounding the brightest Trapezium star θ^1 Ori C. Individual MERLIN 6cm images of the radio emission from the proplyds LV1 and LV2, as well as the Trapezium star θ^1 Ori A are shown as contours.

for the shocked interaction zone between the two proplyd flows, where the high temperature and low density may account for the relative prominence of this region at radio wavelengths. However, it is also possible that some of the radio emission is non-thermal: further EVN observations at 18cm would test this idea, although MERLIN observations at 18cm have yet to achieve sufficient sensitivity to detect this region.

3. Radio emission from θ^1Ori A

At sub-arcsecond resolution, the brightest compact radio source in the Trapezium cluster is (usually) source 12 of Churchwell et al (1987), identified with one of the Trapezium stars θ^1Ori A. The source is highly variable and has been detected on EVN but not transatlantic baselines by Felli et al. (1991), who suggest that the radio emission is associated with a close companion, since θ^1Ori Ais an eclipsing and spectroscopic binary with a 65d period (0.8 AU orbit).

During the MERLIN observations, θ^1Ori A varied between 10 and 50 mJy and was unresolved at 80 mas resolution. As part of the registration of the optical and radio images, it was apparent that there was a significant offset between the optical and radio positions for θ^1Ori A. The simplest expression of this comes from comparing the MERLIN and Hipparcos positions which are both measured independently in the ICRF, and gives an offset of 221±30 mas at P.A. 3±12°. (The route to this realisation was complicated by the fact that almost all recent ground-based optical positions for this regions have been referred to the early VLA positions, which used a less accurate calibrator position, and sometimes used the apparent coincidence of this bright object to fix the co-ordinates.)

This initially puzzling offset is explained by recent infra-red speckle imaging, which finds a second companion star, θ^1Ori A2, separated by 221±5 mas at P.A. −6±2 (Weigelt et al. 1999), exactly the offset seen between the MERLIN and Hipparcos positions. This companion star had first been identified by Petr et al (1998), although at lower resolution, who also speculated that the radio emission might be associated with the companion, θ^1Ori A2.

New global VLBI observations at 6cm, were made in June 2001 using nine VLBA antennas and seven EVN telescopes(Ef,Wb,On,Jb,Mc,Nt,Tr) and correlated by the EVN correlator at JIVE. By phase referencing to 0539-057, which is a defining source of the ICRF, detection and sub-mas astrometry of θ^1Ori A2 was straightforward (see Figure 2). This was helped by the new telescope positions for Jb, Tr and Wb, provided by Charlot et al (these proceedingds). The apparent offset between the MERLIN and VLBI positions may be due to larger errors in the MERLIN position at this low declination, though it may also be partly due to the orbital motion of this star in the 2.5 years between the MERLIN and VLBI observations (see below). Although the object was close to its minimum flux density (10-15 mJy), self-calibration was just possible (see Figure 3. The Westerbork tied array was especially valuable in this regard, since its large collecting area was not compromised by the high background temperature of the Orion Nebula, and it forms some of the longest and shortest baselines in the global network. From these data it would appear that θ^1Ori A2 is just resolved at 2 mas resolution — a model fit to the visibility data gives a size of 1 mas, elongated E-W. Previous VLBI observations, without phase referencing, only detected this object on the intra-European baselines (Felli et al. 1991).

The IR colours of θ^1 Ori A2 give T=8000K and L=100$L_\odot$, placing it on the evolutionary track of a 4-5 $M_\odot$ PMS star at an age of approximately 1 Myr. It is most likely an intermediate-mass analogue to the classical T Tauri stars: a Herbig Ae/Be star. However, Herbig Ae/Be stars are predominantly thermal sources: some have strong ionised winds (Finkenzeller & Mundt 1984); others show radio emission which may arise in an equatorial disk (e.g. MWC 297: Drew et al. 1997). Since they are on radiative PMS tracks they do not possess the convective envelope-spin coupling required for the generation of strong magnetic fields, implied by non-thermal radio emission. Those few objects of this type that show non-thermal emission, e.g., TY Cra, MWC 297 (Skinner et al. 1993) may in fact be misidentified as Herbig Ae/Be stars and, alternatively, represent a new class of intermediate-mass PMS stars.

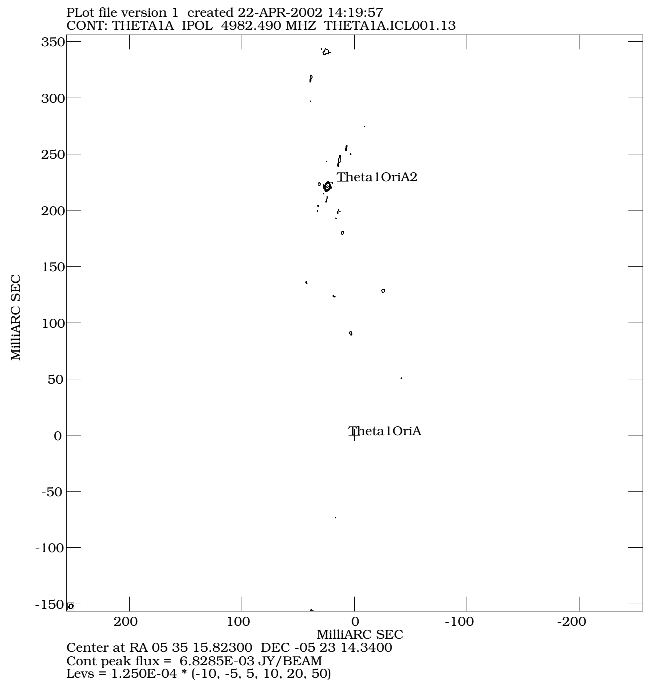

Fig. 2. Global VLBI 6cm phase referenced image showing the detection of θ^1Ori A2, along with the locations of the MERLIN detection and the Hipparcos position for θ^1Ori A.

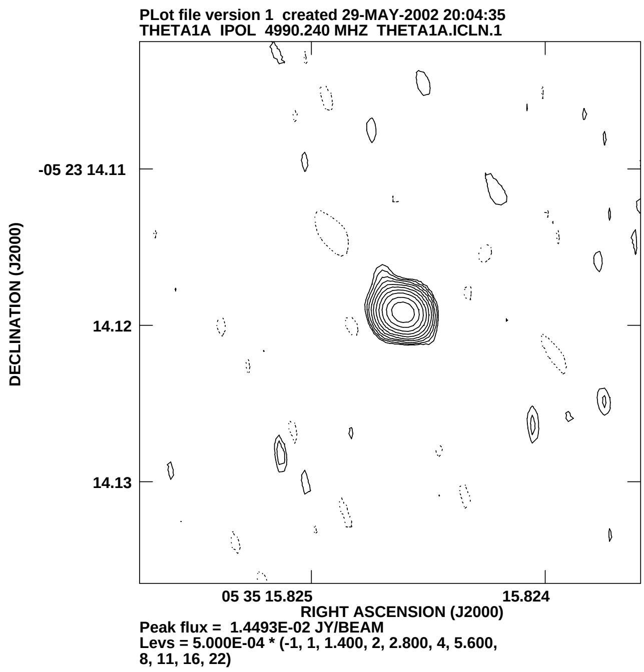

Fig. 3. Global VLBI self-calibrated image of θ^1 Ori A2, restored with a 2 mas circular beam.

θ^1 Ori A2 may be another member of this enigmatic group of objects. Its brightness temperature of 10^8 K confirms the non-thermal nature of its radio emission, though its mass and age suggest it should be a weak thermal source.

Further Global VLBI observations at 1.3cm may provide sufficient resolution to see whether the radio emission has a simple elongated structure, which would support non-thermal emission arising in a star-disk interaction.

4. Future astrometric observations of the θ^1 Ori A system

With several observations appropriately spread over 4 years, it would be possible to measure the orbital parameters of the θ^1Ori A– θ^1Ori A2 system. Assuming that the orbit is face-on and circular, $P_{\rm orb} = 219 \pm 45$ yr, taking $D = 480 \pm 80$ pc and $M_A = 20\ M_\odot$. We should be able to separate the orbital motion from the center-of-mass proper motion to a 3σ level (i.e., detect the effects of $a_{\rm orb}$) after 4 ± 1.2 yr, taking $\sigma_\mu = 0.2$ mas. We can get a feel for $\boldsymbol{\mu}_{\rm CoM}$ by noting that the Hipparcos proper motion for θ^1Ori A is 0 ± 2 mas/yr. The orbital speed of θ^1Ori A is 1.15 ± 0.24 mas/yr; hence $\boldsymbol{\mu}_{\rm CoM}$ must be oppositely directed. This $\boldsymbol{\mu}_{\rm CoM}$ would therefore currently be roughly aligned with the $v_{\rm orb}$ of θ^1Ori A2, 5.2 ± 1.1 mas/yr, but again would be separable within a few years. At $D \sim 480$ pc, the parallax would be $\pi \simeq 2.1$ mas. Current estimates of the distance to the Trapezium Cluster vary between 400 and 500 pc, so obtaining the parallax to < 0.2 mas would provide the most accurate value yet for this distance. (The uncertainty in the Hipparcos parallax is 2 mas.)

Measuring the position of θ^1Ori A2 with an accuracy of ~ 0.2 mas with respect to the ICRF over 6–7 individual epochs over a > 4-yr period should allow simultaneous estimation of $\boldsymbol{r}_0$, $\boldsymbol{\mu}$, π, and a full description of its orbital ellipse (total 10 parameters). The low δ of Orion reduces the N-S resolution, but this can be taken into account with a correlation matrix between the $\Delta\alpha, \Delta\delta$ estimates (Campbell et al. 1996).

5. Conclusions

MERLIN observations have provided some of the most detailed radio images yet of the proplyds in Orion. Further VLBI observations will help to check for sites of non-thermal emission in and around these low mass YSOs.

New global VLBI observations at 6cm confirm that the position of the radio source associated with θ^1 Ori A, is close to the companion star, 220 mas (100 AU) from the primary star, and clearly seen by IR speckle interferometry. The radio emission is barely resolved (~ 1 mas) implying $T_b \sim 10^8$K. The nature of the non-thermal emission from this 4-5$M_\odot$ pre-main-sequence star remains unclear.

Future VLBI observations have the potential to measure the binary orbit of this system and provide an accurate value for the trigonometric parallax.

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