The triple system θ^1 Orionis A in the heart of the Orion Trapezium Cluster

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Summary. Almost two decades ago, strong non-thermal variable radio-emission had been detected from θ^1 Orionis A, the third most luminous OB star in the Orion Trapezium Cluster. The source of the emission, has been a puzzling issue since then. Now, it is established that θ^1 Orionis A is a close triple stellar system and that the radio emission originates from the visual companion θ^1 Orionis A2. In this contribution we re-analyse available radio data combined with near-infrared observations in order to constrain the nature of θ^1 Orionis A2. Stringent constraints on the size of the non-thermal radio emission imply the presence of very large magnetic structures. Conceivable scenarii are a) θ^1 Orionis A2 is a single young intermediate-mass star with strong magnetic interactions between the star and its circumstellar disk, b) θ^1 Orionis A2 is a binary and radio flaring originates from interactions between the magnetic structures of both stars.

1 Introduction

At the center of the famous Orion Nebula Cluster one finds a group of luminous OB stars, which is called the Orion Trapezium. The probably most interesting source among this well studied stars is θ^1 Orionis A (HD 37020), the third most luminous of the Trapezium stars. The spectral classification of θ^1 Orionis A (hereafter θ^1A) is B0.5V [1].

A distinguishing feature detected towards θ^1A is its strong, non-thermal, variable radio-emission that had been found by Churchwell et al. [2]. During repeatedly observed flaring events at 2cm and 6cm wavelengths the source has temporarily been the brightest radio source in the whole Orion Nebula Cluster [3, 4]! Several attempts to explain the origin of the unexpectedly high non-thermal radio emission have been made, including interaction of stellar winds, chaotic wind emission, and a rapidly rotating magnetic star [3, 4, 5]. However, the observations never fully fit with any model predictions, and the nature of the emission remained a puzzling issue. As θ^1A is a close triple stellar system, it has also been difficult to identify which component of the system actually is the radio emitter.

In this contribution we review and re-analyse available radio data in combination with near-infrared observations, and we discuss some scenarii for the enigmatic radio emission from the θ^1A system.

2 Review of available data and facts of θ^1 Ori A

2.1 Multiplicity

For quite some time θ^1A had been thought to be an early type single star, until Lohsen [6] discovered a very close eclipsing companion in 1973. An orbital period of P = 65.4325d has first been derived by [7], and later confirmed and refined by other authors [8, 9]. Furthermore, the mass and evolutionary state of the eclipsing companion was investigated through spectroscopic monitoring, leading [10] to conclude that the eclipsing companion is a T Tauri star of $\sim 2.4 M_\odot$.

Then, in the late 1990s even another, third component was discovered with high angular resolution speckle techniques [11, 12]. This speckle companion is separated from θ^1A by $0.2''$ (~ 90 AU), and we will refer to it as θ^1A2 in the following. At times when the existence of the speckle companion was still unknown, most attempts that have been put forward to explain the nature of the radio-emission [4, 5], involved the close-by eclipsing companion. However, no model did fully satisfactorily fit with the observations. When the speckle companion, θ^1A2, was detected it was obvious to check if θ^1A2 might be the source of the strong radio emission. Positional uncertainties present in the radio data, however, prevented a unique identification. Nevertheless, based on some qualitative arguments and on a positional coincidence at least within 1σ, Petr et al. [11] speculated that θ^1A2 is the radio emitting star.

2.2 Radio observations

The first detection of θ^1Ori A as a radio source [13] and, moreover, as a highly variable strong emitter at 2cm and 6cm wavelengths [2] triggered intensive radio observing campaigns during the following years. Using mainly VLA and VLBI observations, it was confirmed that θ^1Ori A is associated with a high brightness temperature ($T_B \geq 4 \times 10^7$ K) and strong variability, indicating a non-thermal emission [3, 4]. The radio spectral index of θ^1Ori A was on average flat, which allows us to consider in Figure 1 data from 2cm and 6cm observations alltogether. In this Figure 1 we display radio measurements of θ^1Ori A taken over a period of almost 11 years. The plot visualizes the absolute fluxes and the range of the variability, which is of a factor of $\sim$30 between the strongest flare and the quiescent level. Felli et al. [5] also pointed out that the time scale of the variability is similar or smaller than their sampling interval of 10–20 days.

More recent radio observations carried out at $\lambda = 6$cm with MERLIN and global VLBI providing sub-mas astrometry have finally solved the positional uncertainty of the θ^1Ori A radio source: Garrington et al. [14] indisputable associated the radio emission source with the speckle companion θ^1A2; no emission was detected from θ^1A1, the primary OB star (including the eclipsing lower mass TTauri-type companion). Thanks to the improved uv-coverage

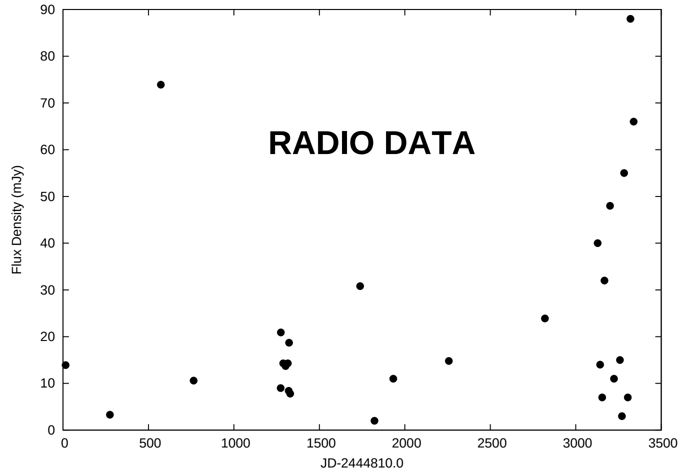

Fig. 1. Radio flux measurements of the source θ^1Ori A as reported in [4, 5] versus date

and sensitivity of the present global VLBI network, these authors were also able to reconstruct a 6cm VLBI image and to determine a source size of $\sim$ 1mas from visibility fitting. The size is roughly consistent with the previously determined size of $\sim$ 1.3mas by [4]. At the distance of the Orion Nebula cluster 1mas corresponds to 0.45 AU or $\sim 90R_{\odot}$, which means a huge emitting source size, and a very important information for constraining the nature of the emission.

2.3 Infrared observations

In order to investigate the stellar characteristics of the radio emitter θ^1A2 we searched the literature for various photometric measurements. Near-infrared system magnitudes (i.e. photometry for the triple θ^1A as a whole) have been collected [15, 11, 16, 17, 18] +2MASS magnitudes. Whenever speckle imaging or adaptive optics techniques were used, we could extract individual near-infrared photometry for both, θ^1A2 and θ^1A1. We also added our own observations obtained with ESO's adaptive optics system ADONIS and from speckle measurements [11].

Surprisingly, we find that the system brightness at J, H, or K-band, as reported by the various authors, shows a large discrepancy (up to $\sim 0.5^{\mathrm{m}}$ at J, $\sim 0.6^{\mathrm{m}}$ at H, $\sim 0.8^{\mathrm{m}}$ at K), which is larger than the typically quoted individual uncertainties. Either the photometry is complicated due to the large crowding in the Trapezium or the source is variable. On the other hand, the brightness ratio of θ^1A1/θ^1A2 is rather consistent across different authors. As there is no good reason why a specific measurement from a certain group of authors should be prefered, we translate the range of photometric results to an uncertainty in the near-infrared colours and magnitudes of θ^1A2. Consequently, the possible space for the radio emitter θ^1A2 in the colour-colour diagram (Fig. 2) and colour-magnitude diagram allows for a number of valid interpretations of its stellar nature.

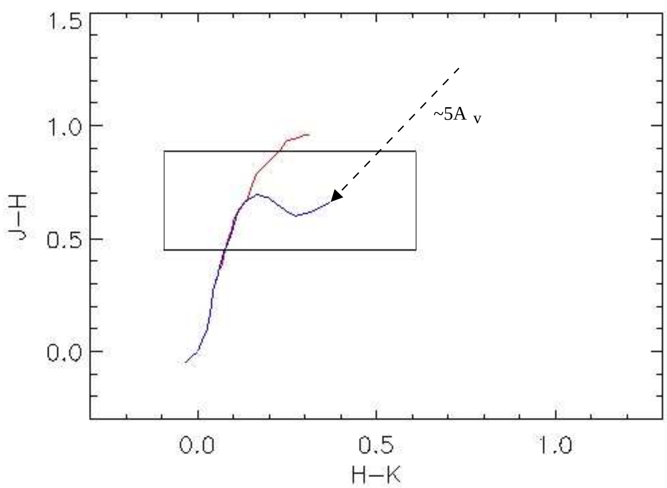

Fig. 2. Near-infrared colour-colour diagram for the star θ^1Ori A2. The box outlines the possible space for θ^1Ori A2 in this diagram. The box is large, because of the large differences in JHK-photometry reported by different authors

From the colour-colour diagram we deduce that θ^1Ori A2 might either be a slightly extincted late-type dwarf or a highly extincted ($A_V > 3$mag) early type star (see also [19]). However, the observed J-band luminosity of θ^1Ori A2 indicates that it is too luminous to be consistent with a young late-type, i.e. low-mass star. Comparing the possible positions of θ^1Ori A2 in the colour-magnitude diagram (shown elsewhere) with pre-main sequence evolutionary tracks by Palla & Stahler [20], we find that θ^1Ori A2 is at least a moderately massive, probably pre-main sequence star with $M_\star > 3.5 M_\odot$. On the other hand, from the photometric information alone, we cannot exclude that θ^1Ori A2 might even be a cool giant, as proposed by [21], although we consider this option less likely.

3 The possible nature of θ^1 Ori A2

In case θ^1Ori A2 is a late-type giant, it would be difficult to explain its evolutionary stage within the 1 Myr old population of the Trapezium Cluster.

In fact, any K or M-giant would be much brighter at JHK than observed, if placed at the distance of the Orion Trapezium Cluster. However, the probability that θ^1Ori A2 is really physically related to θ^1Ori A1 is quite high, disproving suspicions that θ^1Ori A2 is an unrelated object: Given the separation of only $\sim 0.2''$ between θ^1Ori A1 and A2 the probability of the pair being not a chance projection is 99.6%. Furthermore, observations taken over 10 years have shown slight (orbital?) motion of θ^1Ori A2 (Figure 3). Intrinsic JHK luminosities of a G-type giant, on the other hand, seem to be compliant with a distance of ~450pc and the observed JHK brightnesses, but no strong radio continuum emission, like observed for θ^1Ori A2, would be expected.

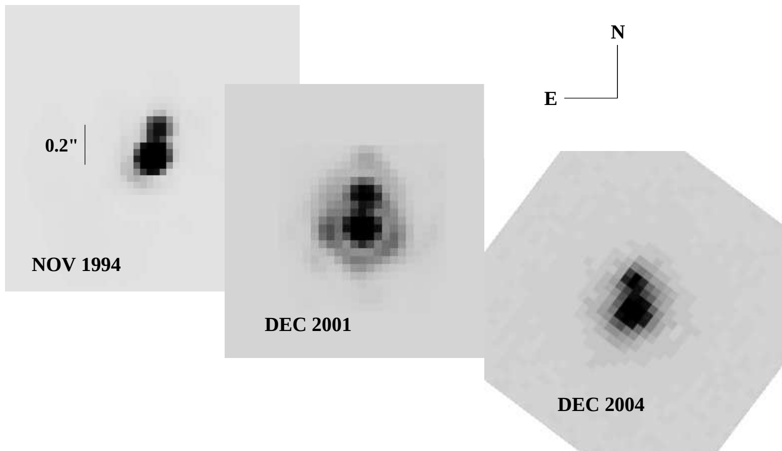

Fig. 3. Orbital motion of θ^1Ori A2 (northern component) around θ^1Ori A1 (southern component). All images show observations in the K-band around 2.2μm. The first image was obtained with the MAGIC camera at Calar Alto observatory via speckle mode. The second image was taken with the adaptive optics system ADONIS on the ESO/3.6m tel. at La Silla Observatory and the third, most recent, observation shows an ESO VLT/NACO acquisition image.

We also exclude that θ^1Ori A2 is an ordinary intermediate-mass Herbig Ae/Be star, since those stars clearly show thermal radio emission, as opposed to the observed non-thermal emission. A magnetic, chemically peculiar star, a class of objects that are often found to be non-thermal radio emitters [22], must be excluded as well, because in this case the radio emission is expected to occur close to the stellar photosphere, which contradicts the enormous size scales found in the VLBI observations. Furthermore, the dynamic range of the radio variability detected for magnetic chemically peculiar stars (up to a few mJy) is much smaller than what has been observed for θ^1Ori A2.

The huge size of the emitting region ($\sim$ 90R$_\odot$) implies that the radio emission from θ^1Ori A2 must arise in "some" magnetic structures located far above the stellar photosphere. Such a structure may be that of a Helmet streamer which can be formed on top of stellar coronal loops and extending out to several tens of the stellar radius [23]. The interaction of the magnetic field confined in such a helmet structure with the magnetosphere of another close-by star can trigger strong radio flaring, as for example has been shown to be a plausible explanation for the non-thermal radio emission in the TTauri binary V773 Tau A [24]. Indeed, a very young ($< 10^6$ Myr) binary system, composed of a low-mass (0.6-2.0$M_\odot$) and an intermediate-mass (3-5$M_\odot$) star would be compliant with the near-infrared photometry of θ^1Ori A2. Possible combinations do certainly depend on the amount of interstellar extinction, which we varied between $A_V = 1 - 4$mag in order to find potential binary pairs. Evidence for the structure of a helmet streamer is further given by the elongation seen in the reconstructed 6cm image of [14].

An alternative single star scenario is that of radio flaring being caused by shearing, disruption and subsequent reconnection of the magnetic fields between a young, chemically peculiar/magnetic, intermediate-mass star and its circumstellar disk [25, 26]. Star-disk interactions are also often invoked to explain high x-ray emission, presumably caused by magnetic activity, from Herbig Ae/Be stars that have not shown to harbour lower mass companions [27]. Non-thermal radio emission is naturally expected. However, to date no apparently single Herbig Ae/Be star has been reported to be a non-thermal radio source (with the probable exception of EC95 [28]). This may, on the other hand, be due to the lack of systematic radio surveys among such stars, in particular among such sources in young stellar clusters.

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