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Discovery of a close companion to the young star Haro 6-37*

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Abstract. We report lunar occultation (LO) and speckle interferometry observations of Haro 6-37, all carried out at λ=2.2 μm. The main finding is the discovery of a new close companion by LO, subsequently confirmed by speckle. The two techniques yield values in excellent agreement, with $0''.331$ and 181° for the separation and position angle respectively. Additionally, the LO data show evidence of what might be interpreted as scattered light from the inner part of the dust disk which is known to exist around Haro 6-37 from mm-radio observations (Osterloh & Beckwith 1995). However this last conclusion is subject to some uncertainty because of possible contamination of the signal during data acquisition. LO and speckle results are in good agreement also for what concerns the brightness ratio of the newly found companion to the main component, R=0.10 or ΔK=2.5. We discuss the possible implications on the general picture of Haro 6-37, in particular for what concerns the ages of the components and the dust disk.

Key words: infrared: stars – stars: pre-main sequence – stars: individual: Haro 6-37 – stars: binaries: close – occultations – techniques: interferometric

1. Introduction

Pre-main sequence (PMS) stars represent the link between the early stages of star formation, and the beginning of life as a normal star on the main sequence. This phase, lasting $\approx 10^5$–10^7 years, is strongly influenced by the initial conditions of the surrounding environment, and characterizes in a significant way the newborn stars in the remaining $\approx 10^6$–10^{10} years of their lifetimes. Therefore, observations of PMS stars play an important role in our understanding of the processes of star formation and stellar evolution, and as such they have been studied with increasing interest at several wavelengths from the X-rays to the radio domains.

In particular, in the past decade it has become increasingly evident that many PMS stars exhibit two important features, namely the presence of circumstellar disks and a binary (or multiple) nature. The circumstellar disks, first inferred from millimeter observations and later observed in some cases also by direct imaging at visual/IR wavelengths, are thought to be the remnant of the original parent condensation. The presence of one or more physically associated companions, on the other hand, is the signature of a common formation process and provides a key to discriminate between the different possible formation mechanism at play. The study of such binary or multiple systems also allows us to make inferences on their evolution in the presence of the complex environment of the parent star forming region (SFR), and once they reach the main sequence. Of particular interest is the understanding of the interactions that take place between the circumstellar (or sometimes circumbinary) disks, and the binary components. This in turn has direct implications on the formation of planetary systems, another topic which is receiving the highest attention in modern observational astronomy. Useful references to many topics related to PMS stars research can by found in the work by Hartmann (1998); recent compilations of PMS multiple stars are given by Ghez (1998) and by Mathieu (1994).

In this line of research, high angular resolution observations in the near-infrared (NIR) play an important role next to the radio and visual ranges. In fact, most radio observations lack the resolution to study the hot, inner parts of the circumstellar disks and to reveal the closest binary components. Observations in the visual range, on the other hand, are severely limited by extinction due to both the circumstellar dust, and the local dust in the surrounding SFR. The typical size of circumstellar disks and binary separations (10–100 AU) are such, that even in the nearest SFRs with a high number of PMS stars (Taurus-Auriga and Scorpius-Ophiuchus, both at ≈ 150 pc), the natural limit in angular resolution set by atmospheric turbulence will limit significantly our ability to investigate their properties. As a consequence, this field of research has seen an increasingly important contribution from high angular resolution techniques such as lunar occultations (e.g. Leinert et al. 1991, Richichi et al. 1994, Simon et al. 1995) and speckle interferometry (e.g. Ghez et al. 1993, Leinert et al. 1993). More recently, also other methods have been successfully employed (e.g. adaptive optics Roddier et al. 1996, Close et al. 1998; speckle holography Petr et al. 1998). Among the main results to be mentioned, is the fact that the frequency of binary systems among PMS stars appears

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* Based on observations collected at the Calar Alto Observatory (Spain), operated by the German-Spanish Astronomical Center.

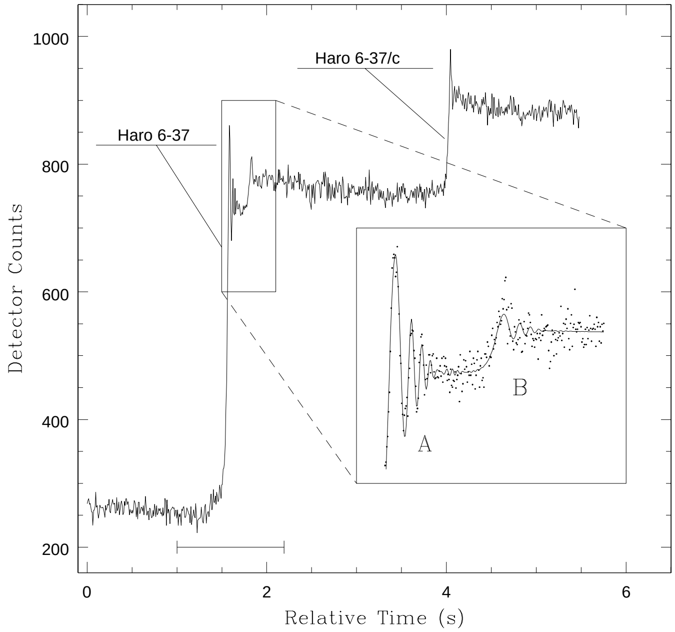

Fig. 1. The larger figure shows a long portion of the occultation trace, including the distant *c* component. These data are rebinned by a factor of 4 to improve the presentation. The inset is an enlargement to show the detection of the newly discovered companion. The occultation data are shown as dots and our fit by a multiple star model as a solid line. The horizontal bar on the bottom marks the portion detailed in Fig. 2.

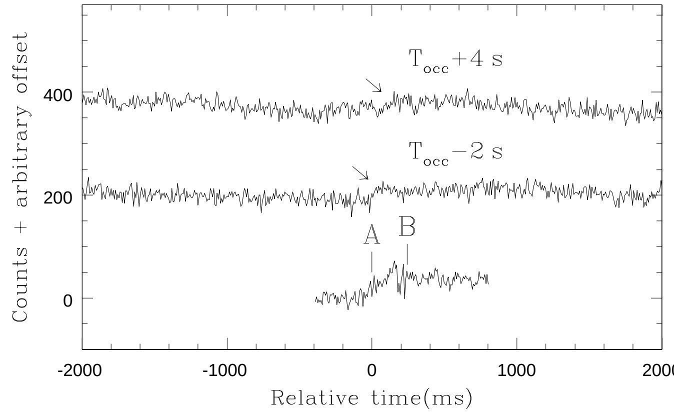

Fig. 2. Comparison of "glitches" in relatively distant portions of the lightcurve (marked by the arrows in the two top curves), with the possible signature of extended emission close to the main component (lower curve). This latter is shown after subtraction of the fringe patterns of the A and B components, whose position is marked. Data rebinned by a factor of 4.

to be significantly higher than for main sequence stars, at least within the limitations of separation range and masses and in the number of stars, which are intrinsic in the currently available surveys. This is true at least for the Taurus-Auriga SFR, to which Haro 6-37 belongs. A detailed discussion was given by Simon et al. (1995). However our conclusions are still limited by the available statistics: in this sense, it is important to increase the numbers of observed binary and multiple systems.

With this work, we report a newly discovered companion around Haro 6-37, which we detected initially by a lunar occultation (LO) event, and subsequently confirmed by speckle interferometry observations.

2. Observations

An occultation of Haro 6-37 was observed on November 16, 1997 at the Calar Alto 3.5 m telescope equipped with an IR fast photometer. This instrument, based on an InSb detector cooled to solid nitrogen temperature, is usually devoted to slit–scanning speckle interferometry, but thanks to its fast time response and large data storage capabilities, it has been successfully employed also to observe LO events, in particular of T Tauri stars (e.g. Leinert et al. 1991, Richichi et al. 1994).

The LO data were recorded with a sampling of 1.95 ms in a standard wide band K filter ($\lambda_0 = 2.36\,\mu$m, $\Delta\lambda = 0.46\,\mu$m). It is shown in Fig. 1, together with our best fit. The fit has been obtained using a least–squares method which is described in Richichi et al. (1992). This approach is well suited to derive the parameters of a simple source model (such as a binary or multiple star). However, when an extended, geometrically complex component is present, a model–independent analysis is necessary. For this, we use an iterative method based on the Lucy's deconvolution algorithm, and expecially designed for LO data (the so-called CAL algorithm, Richichi 1989).

The speckle observations were carried out also at the 3.5 m telescope on Calar Alto shortly after the LO event on November 24, 1997. We used MAGIC, a 256 x 256 pixel NICMOS3 camera (Herbst et al. 1993) in its high-resolution configuration at the f/45 focus, also in the K band. Pixel scale and orientation were determined by astrometric fits to images of the Trapezium cluster, yielding $(0\farcs0710\pm0\farcs0002)/\mathrm{pixel}$ and $-0\fdg28\pm0\fdg05$ respectively. A sequence of 4 groups of 250 frames were recorded on Haro 6-37, each with an integration time of 0.8 s. These groups of fast integrations were alternated with a similar sequence on a nearby point–like reference star, SAO 94117. During data reduction this latter appeared to be itself a binary star, and thus not suitable for calibration. Instead, we used as a reference HIC 19797 (HIC = Hipparcos Input Catalogue), which was similarly observed in the course of the same observational program shortly before Haro 6-37. In spite of an angular distance of $\approx 8°$, the calibration by this star was satisfactory.

The speckle data were processed in order to derive the modulus of the complex visibility (i. e. the Fourier transform of the object brightness distribution) from power spectrum analysis (see Fig. 3). The phase was computed using the Knox-Thompson (1974) algorithm, as well as the bispectrum method (Lohmann et al. 1983). The modulus and phase were then fitted by a triple star model to derive the brightness ratio, separation and position angle of the components. Fits to different subsets of the data give an estimate for the standard deviation of the parameters.

3. Results and discussion

The occultation data shown in Fig. 1 reveal the presence of two companions to Haro 6-37. One of them is the relatively distant

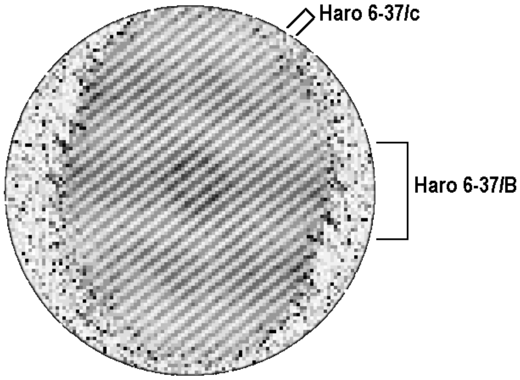

Fig. 3. The modulus of the complex visibility of Haro 6-37, reconstructed from our speckle data. The frequency spacing and orientation of the fringe systems of the two companions are highlighted. The circle is a portion of the Fourier space with a radius of 6.2 arcsec^{-1}.

component firstly discovered by Moneti & Zinnecker (1991) by imaging, and dubbed Haro 6-37/c. Its projected angular distance recovered from the LO data is $\approx 0.''81$, but there is some uncertainty because the occultation rate of this component appears to differ significantly from that of the primary. This is due to the fact that the true separation is quite large (see below). Taking into account the occultation geometry, it turns out that Haro 6-37/c was occulted by a point on the lunar limb 4.4 km away from the primary; this accounts for a significant difference in the local slope of the lunar limb, estimated in about $10°$. At the same time, the distance between the two components is comparable to one-half of the diaphragm ($6''$) used in our LO measurement, making our LO-based estimated of the brightness ratio, R≈0.28, subject to the possible uncertainties of non-uniform detector response across the field. In summary, the relatively large angular distance between these two objects makes it a difficult target for LO. However, Haro 6-37/c is easily resolved in our speckle data, as shown in Fig. 3. These yield a true position angle PA=$38.°6 \pm 0.°1$ and separation ρ=$2.''627 \pm 0.''008$, with a brightness ratio R=0.35±0.01 in K. We note that the LO values are consistent within the uncertainties above mentioned. Haro 6-37/c has been relatively well studied already in the literature, and we will not concern ourselves further with it.

The second, closer component is more interesting, since it represents a new detection. Our fit to the LO data, also shown in Fig. 1, yields a projected separation for the A-B pair $\rho_{\rm P}$=$0.''0857 \pm 0.''0011$ along $\rm PA_{LO}$=$285.°6 \pm 0.°2$, with a brightness ratio R=0.112 ± 0.001 in K. In this case, the vicinity to the primary ensures a very reliable measurement. A model fit to the speckle data with the inclusion of this third component in the system, led to the values PA=$180.°7 \pm 0.°9$, ρ=$0.''331 \pm 0.''005$ and R=0.10 ± 0.02, also in K. It can be noted that the two independent measurements by different techniques are highly consistent, particularly for what concerns the separation. The brightness ratio is slightly discrepant, but we must add that the LO data seem to show the presence of additional extended emission close to the location of Haro 6-37/A.

This was isolated from the fringe patterns of the A and B component and analyzed by the CAL algorithm. The result is consistent with an extended emission of roughly gaussian shape, having a projected FWHM=$0.''075$ and traced out to a total extent of about $0.''2$. This could represent the signature of the inner parts of the dust disk detected by mm-radio observations, but at the same time we must also point out that a few random variations of the background, or DC-offset in the amplification scheme, are also present in the data. Fig. 2 shows some of these variations, compared to the signal which is being tentatively attributed to the extended emission. Although it can be noted that the intensity is at least ≈ 3 times larger for this latter, the order of magnitude and the typical timescales are comparable. Unfortunately, this prevents us to make a definitive conclusion.

One consequence is that also the brightness ratio derived from the LO event must be revised. If the integrated intensity of suspected extended emission (be its nature real or not) is subtracted from that of the A component, the brightness ratios are 1:0.124:0.101 for the A, B and extended components respectively. This brings the LO and speckle determinations for the A-B brightness ration in very good agreement. We also note that such extended emission would be extremely difficult to detect in the speckle observation, causing a slight, slow decrease in the visibility, which we cannot confirm in our data given the available SNR. The brightness ratio of the A-B pair would not be affected, to a first approximation, by the neglection in the fit of such an extended component.

On 9 January 1998, shortly after our LO and speckle observations, K-band photometry of Haro 6-37 was obtained using the NIR camera IRCAM3 at the UKIRT telescope. The derived magnitude were K=(7.92 ± 0.08) mag and K=(8.97 ± 0.08) mag for the central star and the distant companion. From the flux ratio derived above, this leads to K=(8.03 ± 0.09) mag for the A+B component, and K=(10.48 ± 0.09) mag for the newly detected companion. For the purpose of the discussion to follow, it is important to establish whether any variability is present. This is a common feature among T Tauri stars, although it is recognized that its magnitude is more important in the visual than in the near-IR. Hartigan et al. (1994) find that variability causes a mean error of 0.17 mag in the J-band for one component of a binary system. In our case, we can compare our values to the photometry obtained by Moneti & Zinnecker (1991) almost exactly ten years before, giving K=7.71 mag and 8.58 mag for the A+B component and the distant companion, respectively. A decrease of about 0.2 mag is apparent for the A+B component over this time period.

The detection of a new companion is hardly surprising, since it is now well established that young low-mass stars show a high incidence of binary frequency, and particularly so in the Taurus-Auriga SFR as was noted before. Nevertheless this new result has some additional implications, since it makes Haro 6-37 a triple system and because of the presence of a circumstellar disk around it, established by mm-radio observations. In particular, Osterloh & Beckwith (1995) derive a total disk mass of 0.017 $M_\odot$, a characteristic temperature at 1 AU of 130 K, and speak of this system as an "example of a consistent picture of a star and a nearly standard reprocessing disk (q=0.65)".

It is therefore interesting to look into the implications of the newly detected companion for the general picture of this system. It has been pointed out by Simon et al. (1993), that our estimate of the ages of T Tauri stars can be biased up to a factor of 2 by the presence of an undetected companion. Hartigan et al. (1994) have placed Haro 6-37 and Haro 6-37/c into the HR-diagram using the J-band magnitude as luminosity indicator. By comparison with theoretical PMS tracks by D'Antona & Mazzitelli (1994) and Swenson (1994), they find both stars to be coeval with an age of about 6×10^5 yr. The detection of a third component within this system could change this conclusion, only if it had a very red color. In fact, if we assume that the A-B flux ratio is constant between J and K, the J-band brightness of Haro 6-37/A would be overestimated by about 0.10 mag only. This is not significant, given that Hartigan et al. (1994) estimate that variability and interstellar extinction already produce a 0.19 mag uncertainty in the HR-diagram. Also the spectral type of the main component is essentially unaffected, because of the low flux ratio. However, we note that in this regime of masses and ages, the PMS tracks are almost horizontal in the HR-diagram, so that if the color of Haro 6-37/B was significantly redder, this would imply a reduced mass and a larger age for the primary star, and in turn a significant age difference between this latter and the more distant companion. In any case the interesting question remains, if also the newly detected companion is coeval with the two other components. This can be answered when additional spectra and J-band photometry become available.

For what concerns the disk, the new companion does not seem to alter significantly the present understanding of the system. The values derived by Osterloh & Beckwith (1995) indicate a compact dust distribution, with an inner dust formation radius of only 0.013 AU, and a $\tau_{1.3\mathrm{mm}}$=1 radius of 15 AU. By comparison, the newly detected companion is at a distance of ≈46 AU, and this should be considered as a minimum value for the separation in the absence of any orbit determination. Therefore, no real influence on the inner dust disk is to be expected, apart from tidal forces or a clearing of the outer dust, effects which at present are beyond our observational capabilities.

We already mentioned that the additional signal apparent in the LO data, if real, would imply an extended envelope with a projected FWHM=$0\farcs075$ or about 10 AU and about 10% of the intensity of the primary star. The most natural explanation would be that this is scattered light from the above mentioned dust disk, and we note that already in other cases similar detections were obtained by LO. For instance, Leinert et al. (1991) reported an extended emission attributed to scattered light around DG Tau, with FWHM of about 7 AU and 25% of the stellar brightness in K. Additionally, we note that the CAL analysis places this emission approximately in the middle of the A and B components, with the two stars at the edges. This would suggest a circumbinary disk, but the picture is necessarily limited because of the projection effects intrinsic in the LO method.

In conclusion, the newly detected companion does not alter significantly our understanding of the Haro 6-37 system, but it would be interesting to assess more in detail the relative spectral energy distribution of the A and B components, and to obtain a spectrum of this latter. This is at the limit of current observational possibilities, but would be a necessary step to determine whether also Haro 6-37/B is a classical T Tauri star. This would confirm the result of Prato & Simon (1997) who have found that in 12 young binary systems with classical T Tauri behaviour, *both* components are CTTS. Additionally, direct imaging at very high angular resolution of the A and B components could reveal the (circumbinary) disk in scattered light. Haro 6-37/B appears to be ideally suited for observations by the new generation of large ground-based imaging interferometers.

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Note added in proof: After submission of the present work, we became aware of a paper by G. Duchêne (1999), in which the author quotes the discovery of the binarity of the main component of Haro 6-37, observed with adaptive optics by another group (Monin et al., in preparation). The reported result, obtained just one month after our detection, is in very good agreement with the values given in the present work for what concerns angular separation and position angle. Some disagreement with our determination seems to exist for the brightness ratio, which Duchêne reports as ΔK=1.57 ± 0.05.