DIFFRACTION-LIMITED VISIBLE LIGHT IMAGES OF ORION TRAPEZIUM CLUSTER WITH THE MAGELLAN ADAPTIVE SECONDARY ADAPTIVE OPTICS SYSTEM (MagAO)*

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ABSTRACT

We utilized the new high-order (250-378 mode) Magellan Adaptive Optics system (MagAO) to obtain very high spatial resolution observations in “visible light” with MagAO’s VisAO CCD camera. In the good-medium seeing conditions of Magellan (0′′.5–0′′.7), we find MagAO delivers individual short exposure images as good as 19 mas optical resolution. Due to telescope vibrations, long exposure (60 s) images have a large FWHM = 23–29 mas (Strehl ∼28%) with bright (R < 9 mag) guide stars. These are the highest resolution filled-aperture images published to date. Images of the young (∼1 Myr) Orion Trapezium cluster B1 Ori A, B, and C cluster members were obtained with VisAO. In particular, the 32 mas binary B1 Ori C1 C2 was easily resolved in non-interferometric images for the first time. The relative positions of the bright trapezium binary stars were measured with ∼0.6–5 mas accuracy. We are now sensitive to relative proper motions of just ∼0.2 mas yr−1 (∼0.4 km s−1 at 414 pc)—this is a ∼2–10× improvement in orbital velocity accuracy compared to previous efforts. For the first time, we see clear motion of the barycenter of B1 Ori B2 B3 about B1. All five members of the B1 Ori B system appear likely to be a gravitationally bound “mini cluster,” but we find that not all the orbits can be both circular and co-planar. The lowest mass member of the B1 Ori B system (B4; mass ∼0.2 M⊙) has a very clearly detected motion (at 4.1 ± 1.3 km s−1; correlation = 99.9%) w.r.t. B1. Previous work has suggested that B4 and B3 are on long-term unstable orbits and will be ejected from this “mini cluster.” However, our new “baseline” model of the B1 Ori B system suggests a more hierarchical system than previously thought, and so the ejection of B4 may not occur for many orbits, and B3 may be stable against ejection in the long-term. This “ejection” process of the lowest mass member of a “mini cluster” could play a major role in the formation of low-mass stars and brown dwarfs.

Key words: binaries: general – brown dwarfs – instrumentation: adaptive optics – stars: evolution – stars: formation – stars: low-mass

Online-only material: color figures

1. INTRODUCTION

1.1. The Need for High-resolution Imaging

It is critical to the understanding of the motions and masses of stars, brown dwarfs, and exoplanets to obtain the highest resolution images possible. In fact, almost every aspect of astronomical science benefits from the highest spatial resolutions possible. The highest resolution “maps” at the milliarcsec (mas) scales resolution (0′′.001 = 1 mas) are being produced by interferometry (like VLTI/AMBER in the IR). However, interferometric techniques suffer from incomplete uv coverage and object models are usually required to interpret interferometric data. Moreover, combining multiple 8 m telescopes together in the VLTI and waiting for the Earth’s rotation to fill in the uv plane is both time-consuming and expensive (hence limiting the general utility of large surveys with VLTI, for example).

Imaging from space with a filled aperture (and so complete uv coverage) with the Hubble Space Telescope (HST) has proven to be very productive, but HST’s small 2.4 m aperture, combined with a need for large pixels, limits its best spatial resolutions to 50–100 mas. Also, HST is considerably more expensive than any other telescope and its lifetime is limited. Large (8–10 m) ground-based telescopes can match HST’s ∼50 mas V-band resolution with adaptive optics in the NIR (1.2–2.4 μm). For example, the 8.4 m LBT AO system (FLAO; Esposito et al. 2011) can also achieve deep 50 mas resolution images with AO at 1.64 μm (Close et al. 2012b). However, to achieve deep images better than ∼40–50 mas is impossible with the current generation of facility AO systems and cameras. For example, to reach ≤20 mas resolutions at H band (1.65 μm) would require a D ∼16 m filled-aperture telescope. Hence, it will not be until the ELT era (early to mid-2020s) that images in the NIR will be significantly sharper than 20 mas.

1.2. Into the Blue: Adaptive Optics in the Visible

However, there is another approach to reaching these resolutions. While 8–10 m AO performance is limited to ≥40 mas in the NIR, it is possible to gain a factor of two improvement in spatial resolution by moving to shorter (bluer) wavelengths for AO correction. This so-called “visible AO” can theoretically reach 16 mas resolutions on an 8 m telescope at 0.656 μm (Hα). However, the complexity of an 8–10 m class AO system designed for optical wavelengths (>500 modes, at >1 kHz) is beyond that of the current facility systems (with perhaps the exception of the FLAO system on the 8.4 m LBT which, however, currently has no facility visible AO CCD science camera; Esposito et al. 2010).

We note that AO with “lucky” imaging in the visible has been successfully used at the somewhat smaller 5 m Palomar (Law...
et al. 2009) and has reached resolutions of 35 mas, and recently the Palm3000 system has demonstrated excellent corrections (Dekany et al. 2013). Improved Lucky visible imaging (image synthesis based on Fourier Amplitude selection) has also been developed by Garrel et al. (2012). Visible AO has been done before on much smaller telescopes like Robo-AO on the 1.5 m at Palomar (Baranec et al. 2012) or the Villages project on the 1.0m Nickel at Lick (Morzinski et al. 2010). In the near future, some polarization work will be done in the visible with the 8 m Very Large Telescope (VLT) with the SPHERE AO system and ZIMPOL (Bazzon et al. 2012). However, the Magellan Adaptive Optics system (MagAO) is the first large (D \geq 6.5 m) telescope AO system designed to work in the visible—complete with a facility CCD AO science camera (VisAO). The MagAO commissioning results presented here inform us on the utility of large telescope visible AO performance.

1.3. The Magellan AO System

We have developed an AO system (inspired, in large part, by LBT’s FLAO system; Esposito et al. 2012) that can reach 20 mas resolutions with just 250–378 modes at 1 kHz sampling speeds. It is important that such a visible AO system be located at an excellent site where the median seeing is less than 0.64. To achieve an AO fitting error small enough to reach 110 nm rms total wavefront error (WFE) with 250 modes requires a telescope diameter of D \leq 6.5 m. Hence, a solution to this design problem is a fast (\sim1 ms response time) 585 element second generation adaptive secondary mirror (ASM) with a 1 kHz Pyramid wavefront sensor (PWFS). These are exactly the characteristics of the MagAO deployed on the 0.64 median seeing (Thomas-Osip et al. 2010) 6.5 m Magellan telescope at Las Campanas Observatory, Chile.

MagAO, with its VisAO camera,6 is the first large telescope (>6.5 m) facility AO system deployed that is targeting observations in the visible (0.6–1.1 \mu m). As will be shown in later in this paper, MagAO at first light produced long exposure (60 s) diffraction-limited (110 nm WFE; 28% Strehl) 0.63 spotted.5 Seeing (Thomas-Osip et al.2010) 6.5 m Magellan telescope at Las Campanas Observatory, Chile.

MagAO, with its VisAO camera,7 is the first large telescope (>6.5 m) facility AO system deployed that is targeting observations in the visible (0.6–1.1 \mu m). As will be shown in later in this paper, MagAO at first light produced long exposure (60 s) diffraction-limited (110 nm WFE; 28% Strehl) 0.63 \mu m images. Note that during the first light run (commissioning run 1; 2013 November/December) we were limited to 250 corrected modes.7 For more technical details about MagAO, please see Close et al. (2012a).

It is important to note that MagAO sends all the infrared light into the Cli2 NIR (1–5.3 \mu m) camera (Hinz et al. 2010; K. Morzinski et al. 2013, in preparation), whereas the visible light (\lambda < 1.1 \mu m) is split by a selectable beamsplitter between the PWFS and the VisAO (0.6–1.1 \mu m) science camera (for more on the VisAO camera, see Males et al. 2012; Kopon et al. 2013; Close et al. 2012a). Hence all three focal stations (Cli2, VisAO, and PWFS) simultaneously work on all targets, allowing visible and IR observations to be performed simultaneously.

1.4. First Light VisAO Science: Motions of the Massive Young Stars in the Orion Trapezium Cluster

Clearly, the exciting possibility of obtaining \sim 20 mas FWHM images with MagAO could enhance our understanding of the positions (and motions) of the nearest massive young stars. Hence we targeted the Orion Trapezium cluster during the first light commissioning run with the MagAO system.

The study of the motions of the young stars in the Trapezium cluster is an important problem (see, for example, McCarthy & Zuckerman 2004; Close et al. 2012b; Grellmann et al. 2013). After all, the detailed formation of stars is still a poorly understood process. In particular, the formation mechanism of the lowest mass stars and brown dwarfs is uncertain. Detailed three-dimensional (and N-body) simulations of star formation byBate et al. (2002, 2003), Bate (2009, 2012), and Parker et al. (2011) all suggest that stellar embryos frequently form “mini clusters” which dynamically decay, “ejecting” the lowest mass members. Such theories can explain why there are far more field brown dwarfs compared to brown dwarf companions of solar-type stars (McCarthy & Zuckerman 2004) or early M stars (Hinz et al. 2002). Moreover, these theories which invoke some sort of dynamical decay (Durisen et al. 2001) or ejection (Reipurth & Clarke 2001) suggest that there should be wide (>20 AU) very low mass (VLM; M_{\text{tot}} < 0.185 M_{\odot}) binary systems observed in the field (age \sim 5 Gyr). Indeed, the AO surveys of Close et al. (2003a) and the HST surveys of Reid et al. (2001), Burgasser et al. (2003), Bouy et al. (2003), and Gizis et al. (2000) have not discovered more than a few wide (>16 AU) VLM systems in the field population (for a review, see Burgasser et al. 2007). Additionally, the dynamical biasing toward the ejection of the lowest mass members naturally suggests that the frequency of field VLM binaries should be much lower (\leq 5\% for M_{\text{tot}} \leq 0.16 M_{\odot}) than for more massive binaries (\sim 60\% for M_{\text{tot}} \leq 1 M_{\odot}). Indeed, observations suggest that the binaryity of VLM systems with M_{\text{tot}} \sim 0.185 M_{\odot} is 10–15\% (Close et al. 2003a; Burgasser et al. 2003, 2007) which, although higher than predicted, is still lower than that of the \sim 42\% of more massive M dwarfs (Fischer & Marcy 1992) or \sim 60\% of G star binaries (Duquennoy & Mayor 1991). However, as is noted in Close et al. (2007), there is evidence that in young clusters wide VLM binaries are much more common than in the old field population. They attribute this to observing these wide VLM systems before they are destroyed by encounters in their natal clusters. Hence, we need to look at nearby young clusters to see these low-mass objects in “mini clusters” (of a few bound stars) before ejection has occurred.

Despite the success of these decay, or ejection, scenarios in predicting the observed properties of low mass VLM stars and binaries, it is still not clear whether or not “mini clusters” even exist in the early stages of star formation. To better understand whether such “mini clusters” do exist, we have examined the closest major OB star formation cluster for signs of such “mini clusters.” Here we focus on the \theta^{1} Ori stars in the famous Orion Trapezium cluster. Trying to determine if some of the tight star groups in the Trapezium cluster are gravitationally bound is a first step to determining if bound “mini clusters” exist. Also, it is important to understand the true number of real, physical, binaries in this cluster, as there is evidence that the overall number of binaries is lower (at least for the lower mass members) in the dense trapezium cluster compared to the lower density young associations like Taurus-Auriga (McCaughrean 2000; Kohler et al. 2006). In particular, we examine the case of the \theta^{1} Ori A, B and C groups in detail.

The Trapezium OB stars (\theta^{1} Ori A, B, C, D, and E; see Figure 1) consist of the most massive OB stars located at the center of the Orion Nebula star formation cluster (for a review, see Genzel & Stutzki 1989). Due to the nearby (Very Long
Baseline Array trigonometric parallax distance of 414 ± 7 pc; Menten et al. 2007) and luminous nature of these stars, they are a unique laboratory in which to study a high-mass star formation cluster (the dominant birthplace for stars of all masses), and have been the target of several high-resolution imaging studies. For brevity, here we do not reproduce a complete history of past high resolution surveys of Trapezium; see Close et al. (2012b) instead for a review.

Close et al. (2012b) utilized the LBT FLAO system to map out the Trapezium in narrow-band NIR filters at ∼50–60 mas resolutions. In total, Close et al. (2012b) analyzed 14 yr of observations of the cluster. However, only the LBT 2011 observations were of very high quality. In this paper, we present the first high-resolution visible (0.57–0.68 μm) AO images. These images are of the Trapezium cluster and reach very high resolutions of ∼23 mas. We have now over 15 yr of observations of this field with at <0.08 resolution. More importantly, we now have two complete high-quality datasets from LBT and MagAO that track the motion of the Trapezium stars at <0.05 resolutions.

In this paper, we outline how these MagAO observations were carried out with the new VisAO camera. We detail how these data were calibrated and reduced and how the stellar positions were measured. We resolve the 32 mas binary θ1 Ori C in a filled aperture image for the first time. We compare the measured astrometry for θ1 Ori C1 and C2 against its published (interferometric) orbit. We also fit the observed positions to calculate velocities (or upper limits) for the θ1 Ori B1, B2, B3, B4 and A1, A2 stars. While Schertl et al. (2003) and Close et al. (2003b, 2012b) hinted that the θ1 Ori B group may be a bound “mini cluster,” we show that here it is clearly so, with the first detection of curvature in the orbital motion of members of this group. We also present the first model for how the complex set of orbits in the θ1 Ori B mini cluster could (and cannot) be arranged.

2. INSTRUMENTAL SET-UP

We utilized MagAO to obtain the first diffraction-limited (and unsaturated) images of the young stars in the Trapezium cluster in the visible (0.6–0.7 μm). This is not a simple task, since, as telescopes have increased in size, bright stars now tend to saturate even in the shortest possible exposures. Hence, special precautions are needed to avoid saturation of the bright Trapezium stars themselves. It is difficult to make unsaturated, but diffraction-limited, “visible light” images of the bright Trapezium stars with modern 6.5 m class AO systems at even moderately high Strehl. Note that this is the first such dataset ever published. The following subsections outline how this was accomplished.

The MagAO system is unique (at least in the southern hemisphere) in many ways. To reduce the aberrations caused by atmospheric turbulence, all large telescope AO systems have a deformable mirror (DM) which is updated in shape at ∼500 Hz. Except for the MMT AO and LBT AO systems (Wildi et al. 2003; Esposito et al. 2011), all other adaptive optics systems have located this DM at a reimaged pupil (effectively a compressed image of the primary mirror). To reimage the pupil onto a DM typically requires an additional three to eight warm optical surfaces, which significantly increases the optical throughput of the system (Lloyd-Hart 2000). However, MagAO utilizes a next generation adaptive secondary DM. This DM is both the secondary mirror of the telescope and the DM of the AO system. In this manner, there are no additional optics required in front of the science
camera. Hence, the emissivity is lower, and the throughput is higher. MagAO’s DM is an advanced “second generation” ASM (similar to those on the LBT), which enables the highest on-sky visible Strehl (>25% at r’ band; 0.57–0.68 μm) of any large 6.5–10 m telescope today.

The MagAO ASM consists of 585 voice coil actuators that push (or pull) on 585 small magnets glued to the backsurface of a thin (1.6 mm), 850 mm aspheric ellipsoidal Zerodur glass “shell” (for a detailed review of the secondary mirror, see Close et al. 2012a). As in the case of the LBT AO system, we have complete positional control of the surface of this reflective shell by use of a 70 kHz capacitive sensor feedback loop. This positional feedback loop allows one to position an actuator of the deformable shell to within ~5 nm rms (total residual polishing WFEs (mainly at interactuator scales) amount to only ~50 nm rms over the whole secondary). The AO system samples (and drives the ASM) at 990 Hz using 250-378 active controlled modes (with 585 actuators) on bright stars (R < 9 mag).8

The wavefront slopes are measured with a very accurate, well calibrated, low aliasing error PWFS. This is the second large telescope to use a PWFS (after the LBT; Esposito et al. 2011). The performance of the MagAO PWFS is excellent. The very low residual WFEs obtained by the PWFS + ASM combination is due in part to the very accurate (high signal to noise) interaction matrix that can be obtained in closed-loop daytime calibrations with a retro-reflecting calibration return optic (CRO; Kopon et al. 2013) that takes advantage of the Gregorian (concave) nature of the secondary. To guarantee strict “on-sky” compliance with the “daytime calibrated” interaction matrix pupil/ASM/PWFS geometry the PWFS utilizes a novel “closed-loop pupil alignment system” that maintains the pupil alignment to <2.5 μm (at the PWFS CCD39 images of the four pupils produced by the PWFS) during all closed-loop operations on bright stars. Moreover, we use a fixed pupil mask on the ASM to maintain the exact same pupil illumination when the CRO is used and also when we are on sky—so that our interaction matrices are valid (on and off sky). For a detailed review of the MagAO system, see Close et al. (2012a) and references within.

### 2.1. The MagAO PSF and Calculating Strehl

During the MagAO first light commissioning run, we observed the θ1 Ori A, B and C groups on the nights of 2012 December 3, 4, and 8 (UT). The AO system corrected the lowest 250 system modes and was updated at 990 Hz. The PWFS pupil was close-loop stabilized and the shell was protected from wind with a windscreen at the secondary mirror. Cooling pumps (for Clio2, VisAO, and the PWFS) added some vibrational blurring into the point-spread function (PSF). After commissioning run 1 these pumps were much better isolated. Nevertheless, the PSFs were still close to perfectly diffraction-limited. To better gauge the effectiveness of the AO correction, we need to be able to measure the long-exposure PSF and calculate the Strehl of the PSF.

On bright (R < 9) guide stars in ~0.6 V-band seeing we could obtain deep five-minute PSF images (with no SAA or post-detection processing) with Strehls of 43% at Yshort (Y; 0.98 μm), or 140 nm rms WFE (by use of the extended Marechal’s approximation; see Figure 2). We note the deep five-minute image in Figure 2 suffered from some additional vibrational blurring due to the cooling pumps for the CCDs and Clio2.9 These deep PSF images helped model the PSF to calculate Strehls for MagAO on θ1 Ori C which was so bright that only a 64 × 64 CCD window could be readout without saturation on C1. Hence the wings of the PSF (beyond the 64 × 64 window) had to be estimated from a wavelength scaled PSF “halo” model based on the measured deep PSF wings of Figure 2. In this manner, realistic Strehls could be estimated reliably from the small 64 × 64 images of θ1 Ori C1.10 We note that it was only the Strehl of θ1 Ori C1 that required this bootstrap approach; all other Strehls (from full frame CCD images) in this paper were measured in the usual manner by comparison to our model theoretical PSF.

### 2.2. The VisAO CCD AO Science Camera

These observations utilized the first facility visible light AO science camera (VisAO; Males et al. 2012; Kopon et al. 2013). VisAO has a fast, frame transfer, 1024 × 1024 0.5–1.1 μm E2V CCD47 detector. We used the 64 × 64 window mode to minimize saturation on the array while observing θ1 Ori C1 (V = 5.13 mag), while the ~10× fainter θ1 Ori B1 (V = 7.2) allowed the whole CCD to be readout without saturation.

The VisAO focal plane platescales were calibrated by the astrometry of four stars in the HD 40887 quadruple system and θ1 Ori B1 and θ1 Ori E11 (see Sections 3 and 4 for more details about how the images were first reduced).

The positions (found by the IRAF allstar PSF fitting task) of these stars from our VisAO images were compared to unsaturated astrometry from Close et al. (2012b) which itself is derived from the HST Advanced Camera for Surveys (ACS) astrometry of Ricci et al. (2007). VisAO platescales and rms errors were then determined for the Hα, [O i], r′, i′, z′ and Ys filters with the IRAF geomap task. The plate scale found was 0.0078513 ± 0.0000015 pix−1 at Hα (0.656 μm), and [O i] (0.63 μm) providing a 8′′×8′′ field of view (FOV) with our f/52.5 beam on the CCD47’s 13.0 μm pixels. At r′ (0.63 μm) the plate scale was slightly coarser at 0.0079171 ± 0.000015 pix−1, at z′ (0.906 μm) just slightly finer at 0.007911 ± 0.000012 pix−1, and at Yshort (0.982 μm) 0.007906 ± 0.000014 pix−1. By design, the f/16 beam (direct from the ASM) is slowed down to f/52 to yield these very fine 7.9 mas pixel−1 VisAO platescales. We note that this is one of the finest platescales ever for a facility camera.

Small distortions were detected by dithering a binary across the VisAO CCD. In this manner, we detected a small change in the Y platescale (<1%) from the top of the array to the bottom. The exact formula to correct a binary with a primary star at position X,Y of separation δx and δy for any residual distortions is trueδx = measuredδx − δx/(abs(measuredδx)−1/110.0) and

9 For the data collection of Trapezium images in this paper, the vibrating cooling pumps were temporally powered off to help stabilize the images and obtain WFE ~110 nm rms. We note that during the second commissioning run the Clio2 pump was successfully removed from the moving telescope structure and the CCD pump was better isolated from the telescope, greatly reducing residual vibrations.

10 Note that to accurately calculate the Strehl of the θ1 Ori C1 PSF required simply subtracting the PSF of θ1 Ori C1 with the IRAF daophot allstar task.

11 Typically the stars in the Trapezium used for this platescale test move at only ~0′0015 yr−1 so the platescale error over the 624 distance is ~2 × 10−4 error—which is much smaller than the magnitude (~0.1%) of the platescale errors~0′0.06 over this distance.
true$_{\delta y}$ = measured$_{\delta y}$ - $\delta y$/(abs[measured$_{\delta y}$]/44.5) where
$\delta x = -0.00038921676 * (X - 512) + 0.00084322443 * (Y - 512)$ and $\delta y = -0.00025760395 * (X - 512) - 0.0024045175 * (Y - 512)$. Our observations were near the center of the detector and so these corrections were actually very small (0.1%-0.5% or 0.1-5 mas changes to the 0′1-1′ binaries); nevertheless all binary observations in this paper have been fully distortion corrected.

To determine the orientation of the $Y$ axis of the VisAO images (which were all taken with the rotator following) it was first necessary to rotate each image counterclockwise (with the IRAF rotate task) by the ROTOFF FITS keyword value +90 deg. At this point it was found by geomap that the direction of north was slightly (0′890) east of VisAO’s $Y$ axis compared to the $HST$ ACS Ricci et al. (2007) and LBT images (Close et al. 2012b) of the field. Hence a final counterclockwise rotation of -0′890 was applied to the final image. The rms uncertainty adopted for the MagAO rotator angle is estimated as ~0′3 this is the maximum error seen between different images of these stars on different nights. We suspect that this value of ~0′3 is quite conservative based on the very low scatter in the PA fits shown later in this paper.

3. OBSERVATIONS AND REDUCTIONS

For the $\theta^1$ Ori C field we locked the AO system (at 990 Hz, 250 modes) in 0′5-0′7 seeing on the bright O5pv binary star $\theta^1$ Ori C ($V = 5.13$ mag) and used a 64 × 64 window in the center of the VisAO CCD with a set of 2608 × 0.023 s (60 s total) unsaturated exposures at H$_s$, [O I], and $r'$. Immediately following the unsaturated exposures, a set of 60 s exposures were obtained with the AO off. We note that $\theta^1$ Ori C is really a ~0′03 binary composed of C1 and C2 (see Kraus et al. 2007 for more details).

Then the AO system was locked (250 modes, 990 Hz) on $\theta^1$ Ori B1 ($V = 7.96$ mag) and VisAO was used over its fullframe (1k × 1k) pixels to produce a set of 212 × 0.283 s unsaturated (60 s total) images at $z'$.

The individual frames were reduced in a normal manner. We used our custom AO image reduction script of Close et al. (2003a) to sky/bias subtract, cross-correlate (when needed), and median combine each image. The final individual image sets of the C and B fields each had a total exposure time of 1 minute. Figure 1 is a large FOV LBT NIR AO image from Close et al. (2012b) that defines the nomenclature and relative positions of the Trapezium stars for clarity.

In Figure 2, one can see the marked improvement in resolution (~600 mas-34 mas) and Strehl (~0.5%-43%) having the AO loop closed makes to a 300 s exposure. We note these $Y$'s images are not post-detection “frame selected” (lucky imaging) nor shift and added (SAA), so they are true 300 s open-shutter exposures.

In Figure 3, we show typical images of the binary $\theta^1$ Ori C$_1$ and C$_2$ imaged in 0′5 seeing ([O I] and $r'$) on 2012 December 8 and worse 0′7 seeing for H$_s$ on 2012 December 3. In all cases, excellent (26-29 mas and 28%-25% Strehl) images are obtained.

In the middle row of Figure 3, we retrieve the true resolution of the optical beam on the CCD47 by post-detection alignment of the images (~2-4 mas improvement). We also make a similarly small resolution improvement (~2-4 mas) by removing the blurring effects of the CCD47′s pixel response function (PRF). The CCD47′s 13.0 $\mu$m pixel PRF was calibrated by noting the

![Figure 2](image_url)

**Figure 2.** Radial profile (red points) of a deep (300 s) MagAO $Y_{\text{shunt}}$ (0.98 $\mu$m) PSF on a bright ($V = 5$ mag) star closed-loop at 990 Hz with 250 modes in 0′6 $V$ band seeing (from J. R. Males et al. 2013, in preparation). Inset: a log10 Stretch of the PSF. There was no post-detection processing of any of the data (no SAA, no Lucky imaging, or frame selection applied). The theoretical MagAO PSF profile as imaged by the E2V CCD47 (Strehl 100%). A detailed comparison of the observed PSF to theory with our CCD47 (including dark current and PRF) shows that we reached a Strehl of 43% or 140 nm rms optical wavefront error. (A color version of this figure is available in the online journal.)
Figure 3. Top row: the central ionizing binary of the Trapezium: θ1 Ori C as imaged with MagAO’s VisAO CCD camera in different filters. Note the excellent resolution in the raw 60 s image. We note that no post-detection shift and add (SAA) was applied, nor was there any frame selection used to produce these top row images. Typically we achieved resolutions of $0\,\prime\prime\,026–0\,\prime\prime\,029$ and Strehls of 28%–35% in 0′′5–0′′7 V-band seeing. Middle row: the same data as the top row, except the images have been post-detection aligned (SAA) and the pixel response function (PRF) has been removed. This improved image resolution by $\sim 5–6$ mas. Bottom row: the row above is magnified by three times to better display the data of the middle row. These are the highest resolution deep images ever obtained to our knowledge.

(A color version of this figure is available in the online journal.)

slight improvement in FWHM when a lab CCD with smaller 5.5 μm pixels were used (instead of the 13 μm pixels) in a PRF lab test. A similar amount (just slightly less) PRF is observed with HST’s ACS CCDs. Once vibrations and PRF are minimized, the images have 21–23 mas resolutions.

Very short (23 ms) individual images were not effected as much by the residual vibrations and achieved very high resolutions of 21 mas (see Figure 4). These vibrations were found in commissioning to be mainly residual 60 Hz vibrations not corrected by MagAO and are likely due to a few fans on the telescope that we could not turn off. However, once corrected for PRF, these images are diffraction-limited (FWHM = 19 mas; Strehl = 54%; see Figure 4). We do not use Lucky imaging in this study, since the long exposure (60 s) images in Figure 3 are much deeper (and almost as sharp) as those possible to obtain with Lucky in 60 s of telescope time.

4. ASTROMETRY AND PHOTOMETRY

All reduced (with SAA but not PRF-corrected) 60 s images of θ1 Ori C1C2 were analyzed with the DAOPHOT PSF fitting task *allstar* (Stetson 1987). The ±0.48 mas astrometric error of this very tight binary (where our ~0.03 mas platescale errors can be ignored) was estimated by the standard deviation of the astrometry differences between the three filters ([O I], r′, Hα) used. Our θ1 Ori C1C2 measurements of 32.64 ± 0.48 and PA = 206°31 ± 0°17 are compared to the interferometrically derived orbit in Figure 5. We find reasonable agreement between the AO images and the interferometrically derived orbit of Kraus et al. (2009). For θ1 Ori B1, B2, B3, B4 and θ1 Ori A1, A2 the astrometry are summarized in Table 1.

In the θ1 Ori B group the PSF star used was the unsaturated θ1 Ori B1 itself. Since all the members of the θ1 Ori B group are located within 1″ of θ1 Ori B1, the PSF fit is particularly excellent there (there is no detectable change in PSF morphology due to anisoplanatic effects inside the θ1 Ori B group; Diolaiti et al. 2000). Moreover, the residuals over the whole field were less than a few percent after PSF subtraction. This is not really surprising given the quality of the nights combined with the fact that no star was farther than ~1″ from the guide star. However, to minimize this affect, we only used the longer wavelength z′ images reduced with SAA (taken on 2012

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13 While calibrating the throughput of the Hα filter in the second commissioning run, we found a faint companion to the famous transition disk young star HD 142527. The position of this companion at 83 mas and 130° PA was similar to a candidate companion found by aperture masking interferometry at the VLT by Biller et al. (2012), who measured 88 ± 4 mas, 133° ± 3°. Hence, we report for the first time that the existence of the close stellar companion HD 142527B is confirmed as real. Further details about this object are beyond the scope of this work but will be the focus of a future paper (L. M. Close et al., in preparation).
Figure 4. Excellent short exposure single image of θ¹ Ori C at [O I] (630 nm). On the left is the raw image with a resolution of 0″021, Strehl 42%. Then the VisAO CCD’s PRF is removed from the middle box and so the resolution is restored to the true value entering the CCD of 0″019. These are the highest resolution short exposure images ever obtained on any telescope to our knowledge.

(A color version of this figure is available in the online journal.)

Table 1

| System Name | ΔH (mag) | ΔK′ (mag) | Separation (″) | Sep. Vel. (Sep. mas yr⁻¹) | PA (°) | PA Vel. (° yr⁻¹) | Telescope | Epoch (m/d/y) | Notes |
|-------------|----------|-----------|----------------|---------------------------|--------|----------------|------------|---------------|-------|
| B1 B₂       | 2.30 ± 0.15 | 1.31 ± 0.10 | 0.942 ± 0.020 | 254.9 ± 1.0 | 95% corr. | SAO⁴ | 10/14/97 |
|             | 2.07 ± 0.05 | 0.3988 ± 0.0040 | 254.4 ± 1.0 | 1.04 ± 1.0 | 33% no vel. detected | GEMINI | 11/03/98 |
|             | 2.24 ± 0.05 | 0.9375 ± 0.0050 | 254.6 ± 1.0 | 89%; no vel. detected | 0.009 ± 0.043 | | | |
|             |           | 0.9411 ± 0.0023 | 255.1 ± 1.0 | | | | | |
|             |           | 0.9415 ± 0.0014 | 254.55 ± 0.3 | | | | | |
|             |           |              | 254.64 ± 0.3 | | | | | |
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|             |           |              |              | | | | | |
| B₂ B₃       | 1.00 ± 0.11 | 1.24 ± 0.20 | 0.114 ± 0.05 | 204.3 ± 4.0 | 95% corr. | SAO⁴ | 10/14/97 |
|             | 1.04 ± 0.05 | 0.117 ± 0.005 | 205.7 ± 4.0 | 105.8 ± 1.0 | 12/04/12 |
|             |           | 0.1166 ± 0.0040 | 207.8 ± 1.0 | | | | | |
|             |           | 0.1182 ± 0.0030 | 209.7 ± 1.0 | | | | | |
|             |           | 0.1156 ± 0.0005 | 220.39 ± 0.3 | | | | | |
|             |           | 0.1160 ± 0.0002 | 221.50 ± 0.3 | | | | | |
|             |           | -0.04 ± 0.14 | | | | | | |
|             |           |              | 24%; no vel. detected | | | | | |
|             |           |              | 1.19 ± 0.06 | | | | | |
|             |           |              | 4.7 ± 0.2 km s⁻¹ | | | | | |
|             |           |              | corr.=99.9% | | | | | |
| B₁ B₄       | 5.05 ± 0.8 | 5.01 ± 0.10 | 0.609 ± 0.008 | 298.0 ± 2.0 | 95% corr. | SAO⁴ | 02/07/01 |
|             | 4.98 ± 0.10 | 0.6126 ± 0.0040 | 298.2 ± 1.0 | | | | | |
|             |           | 0.6090 ± 0.0050 | 298.4 ± 1.0 | | | | | |
|             |           | 0.6157 ± 0.003 | 300.1 ± 0.5 | | | | | |
|             |           | 0.6182 ± 0.0009 | 300.23 ± 0.3 | | | | | |
|             |           | 0.72 ± 0.23 | | | | | | |
|             |           | 1.4 ± 0.5 km s⁻¹ | | | | | | |
|             |           | 0.181 ± 0.067 | | | | | | |
|             |           | 3.83 ± 1.27 km s⁻¹ | | | | | | |
|             |           | corr.=99.9% | | | | | | |
| A₁ A₂       | 1.51 ± 0.15 | 1.38 ± 0.10 | 0.208 ± 0.030 | 343.5 ± 5.0 | 95% corr. | Calar Alto⁶ | 11/15/94 |
|             | 1.51 ± 0.05 | 0.2215 ± 0.0005 | 353.8 ± 2.0 | | | | | |
|             | 1.62 ± 0.05 | 0.2051 ± 0.0030 | 356.9 ± 1.0 | | | | | |
|             |           | 0.1931 ± 0.0005 | 366.5 ± 0.3 | | | | | |
|             |           | 0.1881 ± 0.0016 | 367.6 ± 0.3 | | | | | |
|             |           | -1.6 ± 0.2 | | | | | | |
|             |           | -2.3 ± 0.3 km s⁻¹ | | | | | | |
|             |           | corr.=92.9% | | | | | | |
|             |           | 0.98 ± 0.07 | | | | | | |
|             |           | 6.3 ± 0.4 km s⁻¹ | | | | | | |
|             |           | corr. = 99.4% | | | | | | |

Notes.

⁴ Speckle observations of Weigelt et al. (1999).
⁵ These low ΔK′ values are possibly due to θ¹ Ori B₁ being in eclipse during the 11/03/98 observations of Weigelt et al. (1999).
⁶ Note there is velocity detected from B₁ w.r.t. the barycenter of the B₂ B₃ binary; see Figures 10 and 11.
⁷ Speckle observations of Scherdl et al. (2003).
⁸ Speckle observations of Petr et al. (1998).
⁹ A₁ A₂ Data from Ks image from the MagAO/Clio2 NIR camera (K. Morzynski et al. 2013, in preparation).
December 4) where anisoplanatic PSF effects were undetected. The relative positional accuracy is an excellent \( \sim 0.2 - 1.4 \) mas in radial separation. The \( \sim 0.2 - 1.4 \) mas separation errors are the resultant of the platescale uncertainty added in quadrature with the measurement uncertainty (FWHM/(S/N)). The errors are somewhat worse in the PA direction (0.6–5 mas) due to a fixed \( \pm 0.3 \) deg conservative estimate of our absolute rotator uncertainty.

We can also compare our MagAO data to older (somewhat less accurate) images of the Trapezium B stars from Close et al. (2003b) who used AO images from Gemini and the 6.5 m MMT and speckle images from the literature (Scherf et al. 2003). Even though these individual observations are of lower quality and Strehl than the MagAO ones (compare Figures 6–8 to that of MagAO in Figure 9), the 15 years between these observations and those of MagAO can highlight even very small orbital motions of bound systems in the Trapezium. It also shows the very significant improvement in high Strehl AO now possible with PWFS and next generation ASMs.

A test to see how accurate our astrometry is over the last 15 yr is to look at the scatter from a linear trend of the \( \theta^1 \) Ori B group’s motions. A comparison of our highly accurate positions with the historical positions from the literature is summarized in Table 1. Linear (weighted by astrometric error) fits to the data in Table 1 (Figures 10–15) yield the velocities shown in Table 1. The overall error in the relative proper motions is now an impressive \( \lesssim 0.2 \) mas yr\(^{-1}\) in proper motion (\( \lesssim 0.4 \) km s\(^{-1}\)), a factor of 2 improvement in accuracy when the VisAO positions are added into these calculations, compared to the last published values from Close et al. (2012b).

5. ANALYSIS AND DISCUSSION

With these accuracies it is now possible to determine whether these stars in the \( \theta^1 \) Ori B group are bound together, or merely chance projections in this very crowded region. We adopt the masses of each star from the Siess Forestini &Dougados (1997); Bernasconi & Maeder (1996) tracks fit by Weigelt et al. (1999) where we find masses of: \( B_1 \sim 7 \) M\(_{\odot}\), \( B_2 \sim 3 \) M\(_{\odot}\), \( B_3 \sim 2.5 \) M\(_{\odot}\), \( B_4 \sim 0.2 \) M\(_{\odot}\), \( B_5 \sim 7 \) M\(_{\odot}\), \( A_1 \sim 20 \) M\(_{\odot}\), \( A_2 \sim 3 \) M\(_{\odot}\), and \( A_3 \sim 2.6 \) M\(_{\odot}\). Based on these masses (which are similar to those adopted by Schertl et al. 2003) we can comment on whether the observed motions are less than the escape velocities expected for simple face-on circular orbits.

Our combination of high spatial resolution and high signal to noise shows that there is very little significant motion in the
$B_1 B_2$ system over the last 15 years (as we might expect since the rotation of $B_2$ about the barycenter of the $B_1 B_2 B_3$ system appears to be just canceling the motion of $B_2$ w.r.t. $B_1$). But of course, it is really the barycenter of the tight $B_2 B_3$ binary that would be in orbit around $B_1$. Hence the barycenter would have to show steady orbital motion if bound to $B_1$. Since $B_2$ is only 20% more massive than $B_3$, this means the $B_2 B_3$ barycenter is currently 52 mas at PA $221.5$ from the center of $B_2$. In Figures 10 and 11, we see that there is a small yet significant motion of the barycenter of $B_2 B_3$ w.r.t. $B_1$ of some $0.80 \pm 0.18$ mas yr$^{-1}$ ($1.6 \pm 0.3$ km s$^{-1}$) and in PA by $0.030 \pm 0.044$ yr$^{-1}$ ($1.0 \pm 1.0$ km s$^{-1}$). Hence the motion of $B_2 B_3$ is currently about $1.9 \pm 0.6$ km s$^{-1}$ in the direction of PA $\sim 305^\circ$ (moving toward the WNW direction from $B_1$). This is the first time this motion has been detected.

At this time it is not yet possible to prove that this is true orbital motion, but, given how close $B_2 B_3$ is to $B_1$, this is likely orbital motion.

We have, of course, observed clear orbital motion (at $4.7 \pm 0.2$ km s$^{-1}$) in the very tight $\theta^1$ Ori $B_2 B_3$ system in almost pure PA (see Figure 13). In fact, now that we have observed over 20$^\circ$ of PA rotation (with no significant change in separation), we have clear evidence of an “arc” of the curvature of the system. The motion of the $B_2 B_3$ binary is roughly consistent with a face-on, circular orbit (orbiting in the counterclockwise direction). A mildly elliptical orbit is also quite plausible given the very small amount of orbital phase observed to date.

We also see linear orbital motion of $7.0 \pm 0.5$ km s$^{-1}$ in the $\theta^1$ Ori $A_1 A_2$ system (see Table 1). This is consistent with the motion seen by Grellmann et al. (2013). We know that this is likely orbital motion since it is higher than the motion of unrelated stars in the cluster due to their very close separation of just $0.19$.

5.1. Is the $\theta^1$ Ori $B_2 B_3$ System Physical?

The relative velocity in the $\theta^1$ Ori $B_2 B_3$ system (in the plane of the sky) is now more accurate by $\sim 10 \times$ compared to that of Close et al. (2003b) and by $\sim 2 \times$ compared to Close et al. (2012b). Our new velocity of $4.7 \pm 0.2$ km s$^{-1}$ is consistent, but with much lower errors, with the $\sim 4.2 \pm 2.1$ km s$^{-1}$ of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8}
\caption{LBT AO Br$\gamma$ (2.16 \(\mu\)m) images of the $\theta^1$ Ori B group. Resolution 0\'.06. Logarithmic color scale. North is up and east is to the left. Strehl is $\sim 75\%$ (from Close et al. 2012b). (A color version of this figure is available in the online journal.)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9}
\caption{MagAO $z'$ (0.91 \(\mu\)m) images of the $\theta^1$ Ori B group. Resolution 0\'.034. Linear color scale. North is up and east is to the left. Note that this image is $\sim 2 \times$ sharper than that of the 8.4 m LBT at Br$\gamma$ (2.16 \(\mu\)m; see Figure 8). This is clear evidence that AO in the “blue” allows a smaller 6.5 m telescope to outperform the resolution of an 8 m in the NIR. (A color version of this figure is available in the online journal.)}
\end{figure}
5.2. Is the $\theta^1$ Ori B Group Stable Long Term?

The barycenter of $B_2B_3$ is moving at a low $1.9 \pm 0.6$ km s$^{-1}$ in the plane of the sky w.r.t. to $B_1$ (itself a very tight pair with $B_3$) where the escape velocity $V_{\text{esc}} \sim 6$ km s$^{-1}$ for this massive system ($\sim 20 M_{\odot}$). Hence these two pairs are likely gravitationally bound together. This is the first effort that has measured this small barycenter velocity definitively. Hence, we can say that these two pairs currently form a rare bound “mini cluster” of young massive stars.

5.2.1. Is the Orbit of $\theta^1$ Ori B4 Stable?

The two AO measurements of (Close et al. 2003b; and the one speckle detection of Schertl et al. 2003) did not detect a significant velocity of $B_4$ w.r.t. $B_1$: $2 \pm 11$ km s$^{-1}$. However, our much better data and timeline between the LBT epoch and
6.47 day massive (given an average angular velocity of 0
expect a very rough period of counterclockwise). Assuming a simple face-on orbit, we would question of B4 orbiting B1. As is clear from Figures 14 and 15, the excellent MagAO observations has shed some light on the orbital “arcs” imaged so far over the last 15 yr for the system. Clearly the orbits are still undefined, but this plot gives some insight into the nature of the system. (A color version of this figure is available in the online journal.)

Figure 14. Separation between θ1 Ori B1 and B4. Note how over 13 yr of observation there is little change in the separation (0.72 ± 0.23 mas yr⁻¹, correlation 95%). The first data point is an speckle observation from the 6 m SAO telescope (Schartl et al. 2003), then Gemini/Hokupa’a observation (Close et al. 2003b), the next data point is from the MMT AO observation (Close et al. 2003b), the next from the LBT (Close et al. 2012b), and the last is from MagAO. (A color version of this figure is available in the online journal.)

Figure 15. Position angle between θ1 Ori B1 and B4. Note how over 13 yr of observation there has been only now clear significant relative proper motion observed (0′.181 ± 0′.067 yr−1; correlation 99.8%). The sources of the data are the same as in Figure 14.
(A color version of this figure is available in the online journal.)

5.3. A Possible Model for the Orbits of the θ1 Ori B Group

It is tempting to define a circular orbit baseline model of the θ1 Ori B system with the center as the very tightly bound 6.47 day massive (∼14 M⊙) 0.13 AU spectroscopic binary B1 B5 which we cannot spatially resolve. Around this center is the low mass 0.2 M⊙ B4 some ∼254 AU away which orbits every ∼2000 ± 700 yr in a roughly face-on circular orbit. Then, farther out, the tight 49 AU binary B2 B3 rotates every 302 ± 16 yr around its barycenter with roughly a face-on circular orbit. However, the co-planar geometry is broken by the orbit of this barycenter around B1. It appears that the B2 B3 barycenter is moving in a bound orbit to WNW (PA ∼ 305°). This motion cannot be in a simple face-on circular orbit, and so must be (if close to circular) inclined by about ∼30°, but many other elliptical orbits are also possible. We simply do not have enough time baseline to understand the fine details of this orbit today. If we simply assume that it is an inclined circular orbit then it has roughly a ∼820 AU (deprojected) separation from B1 and a period of some ∼11,000 yr.

Refer to Figures 16 and 17 for illustrations of what these orbits would look like if they are all close to circular. It is interesting to note that once the true (deprojected) separation of B3 B2 is considered, the group seems more hierarchical than reported in Close et al. (2012b). For example, the ratio of the three main periods are P23/P141/P123 = 1:7:36 so that there is almost an order of magnitude separating each period. This large spread of orbital periods will lend some stability to this “mini-cluster.” On the other hand, B4’s VLM, its intermediate period, and its location w.r.t. to the other four groups members makes it highly unlikely that B4 is on a long-term stable orbit within the group. It is very likely that an interaction between the much more massive B2 B3 and B4 will eject B4 in the future—leading to a slightly more tightly bound “mini cluster” without B4. As we will discuss in the next section, even the much more massive B3 may not even be stable in the long-term.

5.3.1. Is the Orbit of B1 around B2 and of B5 around B1 Stable in the Long-term?

Close et al. (2012b) noted that the distance DB1B5 ∼ 3 × 10⁻⁴ × DB2B1DB3B5 and thus the very tight (0.13 AU) tight B1 B5 system is, of course, very stable. More interesting is the case of B2 B3. Their deprojected distance is not very small compared to their projected distance (D) from the B1 B5 pair: DB1B5 ∼
0.06 × DA/B/C/B. Thus the stability of the B2B orbit needs a more detailed analysis since it is possible that B3 may be ejected in the future.

The orbital period of the two binaries w.r.t. each other is

\[ P_{1/23} \approx 11,000 \text{ yr} \]

while the orbital period of B3 w.r.t. B2 amounts to

\[ P_{2/3} \approx 300 \text{ yr} \]

For the calculation of both periods, we have assumed the masses as given above, and circular orbits in the plane of the sky (except for B1B2 which is inclined at \( \sim 30^{\circ} \)). This leads to a period ratio

\[ X = P_{1/23}/P_{2/3} \approx 36 \]

Eggelton & Kiseleva's stability criterion requires

\[ X \geq X_{\text{crit}} = 10.08 \]

for the masses in the B group. This means that within the accuracy limits of our investigation, the binary B2B3 is likely stable (different from the marginal stability found in Close et al. 2012b). The stability criterion depends also on the orbits' eccentricities. However, mild eccentricities of the order of \( e \approx 0.1 \) (as can be expected to develop in hierarchical triple systems; see, e.g., Georgakarakos 2002) can make the B group unstable. However, the \( \theta^1 \) Ori B system seems to be a good example of a highly dynamic star formation "mini cluster" which might, in the future, eject the lowest-mass member(s) through dynamical decay (Durisen et al. 2001).

6. CONCLUSIONS

In this study, we utilized the new high-order (585 actuator) MagAO to obtain very high-resolution science in the visible with MagAO’s VisAO CCD camera. In the median seeing conditions of Magellan (0.5–0.7), we found that MagAO delivers individual short exposure images as good as 19 mas optical resolution. Due to residual 60 Hz vibrations, long exposure (60 s) \( r' \) (0.63 \( \mu \)m) images are slightly coarser at FWHM = 23–29 mas (Strehl ~28%) with bright (\( R < 9 \) mag) guide stars. These are the highest resolution filled-aperture images published to date. Images of the young (\( \sim 1 \) Myr) Orion Trapezium \( \theta^1 \) Ori A, B, and C cluster members were obtained with the VisAO camera. In particular, the 32 mas binary \( \theta^1 \) Ori C1C2 was easily resolved in non-interferometric images for the first time. Relative positions of the bright trapezium binary stars were measured with 0.6–5.0 mas accuracy. We now are sensitive to relative proper motions of just \( \sim 0.2 \) mas yr\(^{-1} \) (\( \sim 0.4 \) km s\(^{-1} \) at 414 pc)—this is a \( \sim 2–10 \times \) improvement in velocity accuracy compared to previous efforts. We now detect clear orbital motions of \( \theta^1 \) Ori B2B3 and \( A_1A_2 \) of 4.7 ± 0.3 km s\(^{-1} \) and 7.1 ± 0.5 km s\(^{-1} \), respectively. For the first time, we see clear motion of the barycenter of \( \theta^1 \) Ori B2B3 in about \( \theta^1 \) Ori B1. All five members of the \( \theta^1 \) Ori B system appear likely a gravitationally bound "mini cluster," but we find that not all the orbits can be both circular and co-planar. The very lowest mass member of the \( \theta^1 \) Ori B system appears to be on a marginally stable orbit given its somewhat lower mass (~0.2 M\(_{\odot}\)) has a very clearly detected motion (at 4.1 ± 1.3 km s\(^{-1} \), correlation = 99.9%) w.r.t. B1. Previous work has suggested that B1 and B2 are both on long-term unstable orbits and will be ejected from this "mini cluster." However, our new "baseline" model of the \( \theta^1 \) Ori B system suggests a more hierarchical system than previously thought, and so the ejection of B2 may not occur for many orbits, and B1 may be stable against ejection long-term. This “ejection” process of the lowest mass member of a “mini cluster” could play a major role in the formation of low mass stars and brown dwarfs.

7. FUTURE OBSERVATIONS

Future observations are required to see if indeed these stars continue to follow orbital arcs around each other proving that they are interacting with one another. In addition, future observations of the \( \theta^1 \) Ori B1 positions would help deduce if it is on a marginally stable orbit given its somewhat "non-hierarchical" location in the B group.

Future observations should also try to determine the radial velocities of these stars. Once radial velocities are known, one can calculate the full space velocities of these stars. Such observations will require both very high spatial and spectral resolutions. This might be possible with instruments such as the AO fed ARIES echelle instrument at the MMT.

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