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HIGH RESOLUTION IMAGES OF ORBITAL MOTION IN THE TRAPEZIUM CLUSTER: FIRST SCIENTIFIC RESULTS FROM THE MMT DEFORMABLE SECONDARY MIRROR ADAPTIVE OPTICS SYSTEM[1]

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ABSTRACT

We present the first scientific images obtained with a deformable secondary mirror adaptive optics system. We utilized the 6.5m MMT AO system to produce high-resolution (FWHM=0.07″) near infrared ($1.6\mu m$) images of the young (~ 1 Myr) Orion Trapezium θ^1 Ori cluster members. A combination of high spatial resolution and high signal to noise allowed the positions of these stars to be measured to within $\sim 0.003''$ accuracies. We also present slightly lower resolution (FWHM$\sim$0.085″) images from Gemini with the Hokupa'a AO system as well. Including previous speckle data (Weigelt et al. 1999), we analyze a six year baseline of high-resolution observations of this cluster. Over this baseline we are sensitive to relative proper motions of only $\sim 0.002''$/yr (4.2 km/s at 450 pc). At such sensitivities we detect orbital motion in the very tight θ^1 Ori B_2B_3 (52 AU separation) and θ^1 Ori A_1A_2 (94 AU separation) systems. The relative velocity in the θ^1 Ori B_2B_3 system is 4.2 ± 2.1 km/s. We observe 16.5 ± 5.7 km/s of relative motion in the θ^1 Ori A_1A_2 system. These velocities are consistent with those independently observed by Schertl et al. (2003) with speckle interferometry, giving us confidence that these very small ($\sim 0.002''$/yr) orbital motions are real. All five members of the θ^1 Ori B system appear likely gravitationally bound (B_2B_3 is moving at ~ 1.4 km/s in the plane of the sky w.r.t. B_1 where $V_{esc} \sim 6$ km/s for the B group). The very lowest mass member of the θ^1 Ori B system (B_4) has $K' \sim 11.66$ and an estimated mass of $\sim 0.2 M_\odot$. There was very little motion (4 ± 15 km/s) detected of B_4 w.r.t B_1 or B_2, hence B_4 is possibly part of the θ^1 Ori B group. We suspect that if this very low mass member is physically associated it most likely is in an unstable (non-hierarchical) orbital position and will soon be ejected from the group. The θ^1 Ori B system appears to be a good example of a star formation "mini-cluster" which may eject the lowest mass members of the cluster in the near future. This "ejection" process could play a major role in the formation of low mass stars and brown dwarfs.

Subject headings: instrumentation: adaptive optics — binaries: general — stars: evolution — stars: formation — stars: low-mass, brown dwarfs

1. INTRODUCTION

The detailed formation of stars is still a poorly understood process. In particular, the formation of the lowest mass stars and brown dwarfs is uncertain. Detailed 3D simulations of star formation by Bate et al. (2002) suggest that stellar embryos form into "mini-clusters" which dynamically decay "ejecting" the lowest mass members. Such theories can explain why there are far more field brown dwarfs (BD) compared to BD companions of solar type stars (McCarthy et al. 2003) or early M stars (Hinz et al. 2002). Moreover, these theories which invoke some sort of dynamical decay (Durisen, Sterzik, & Pickett 2001) or ejection (Reipurth & Clarke 2001) suggest that there should be no wide (> 20 AU) very low mass (VLM; $M_{tot} < 0.185 M_\odot$) binary systems observed. Indeed, the AO surveys of Close et al. (2003a) and the HST surveys of Reid et al. (2001a); Burgasser et al. (2003); Bouy et al. (2003); Gizis et al. (2003) have not discovered any wide (> 16 AU) VLM systems of the 34 systems known to date. As well, the dynamical biasing towards the ejection of the lowest mass members naturally suggests that the frequency of VLM binaries should be much less ($\lesssim 5\%$ for $M_{tot} \sim 0.16 M_\odot$) than for more massive binaries ($\sim 60\%$ for $M_{tot} \sim 1 M_\odot$). Indeed, observations suggest that the binarity of VLM systems with $M_{tot} \lesssim 0.185 M_\odot$ is $10-15\%$ (Close et al. 2003a; Burgasser et al. 2003) which, although higher than predicted is still lower than that of the $\sim 60\%$ of G star binaries Duquennoy & Mayor (1991).

Despite the success of these decay or ejection scenarios in predicting the observed properties of binary stars, it is still not clear that "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 θ^1 Ori stars in the 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" ex-

[1] A portion of the results presented here made use of the of MMT Observatory, a facility jointly operated by the University of Arizona and the Smithsonian Institution.

ist. In particular, we will examine the case of the θ^1 Ori B and A groups.

The Trapezium OB stars (θ^1 Ori A, B, C, D, and E) consists 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 luminous nature of these stars they have been the target of several high-resolution imaging studies. Utilizing only tip-tilt compensation McCaughrean & Stauffer (1994) mapped the region at K' from the 3.5-m Calar Alto telescope. They noted that θ^1 Ori B was really composed of 2 components (B_1 & B_2) about $\sim 1''$ apart. Higher $\sim 0.15''$ resolutions were obtained from the same telescope by Petr et al. (1998) with speckle holographic observations. At these higher resolutions Petr et al. (1998) discovered that θ^1 Ori B_2 was really itself a $0.1''$ system (B_2 & B_3) and that θ^1 Ori A was really a $\sim 0.2''$ binary (A_1 & A_2). A large AO survey of the inner 6 square arcminutes was carried out by Simon, Close, & Beck (1999), who discovered a very faint (100 times fainter than B_1) object (B_4) located just $0.6''$ between B_1 and B_2. Moreover, a spectroscopic survey (Abt, Wang, & Cardona 1991) showed that B_1 was really an eclipsing spectroscopic binary (B_1 & B_5; sep. 0.13 AU; period 6.47 days). As well, θ^1 Ori A_1 was also found to be a spectroscopic binary (A_1 & A_3; sep. 1 AU; Bossi et al. (1989)). Weigelt et al. (1999) carried out bispectrum speckle interferometric observations at the larger Russian SAO 6-m telescope (2 runs in 1997 and 1998). These observations showed θ^1 Ori C was a very tight $0.033''$ binary. These observations also provided the first set of accurate relative positions for these stars. Schertl et al. (2003) has continued to monitor this cluster of stars and has independently detected an orbital motion (of $\Delta PA \sim 6°$ for θ^1 Ori A_2 around A_1 and a ΔPA of $\sim 8°$ for θ^1 Ori B_3 around B_2 over a 5.5 yr baseline). They conclude that this is real orbital motion. We present additional recent AO observations of these binaries as an independent check to confirm that these motions are indeed real.

We first utilized the Gemini telescope (with the Hokupa'a AO system) and then observed θ^1 Ori B during commissioning of the world's first secondary deformable mirror at the 6.5-m MMT telescope. In this paper we outline how the observations were carried out, and how the stellar positions were measured. We fit the observed positions to calculate velocities (or upper limits) for the θ^1 Ori B & A stars. In agreement with Schertl et al. (2003), we find that there is good evidence that the θ^1 Ori B group may be a bound "mini-cluster" and that the θ^1 Ori A group is also likely gravitationally bound.

2. OBSERVATIONS

We have utilized the University of Arizona adaptive secondary AO system to obtain the most recent high resolution images of the young stars in the Trapezium cluster (the θ^1 Ori group).

2.1. *The World's First Adaptive Secondary AO System Scientific Results*

The 6.5 m MMT telescope has a unique adaptive optics system. To reduce the aberrations caused by atmospheric turbulence all AO systems have a deformable mirror which is updated in shape at ~ 500 Hz. Until now all adaptive optics systems have located this deformable mirror (DM) at a re-imaged pupil (effectively a compressed image of the primary mirror). To reimage the pupil onto a DM typically requires 6-8 warm additional optical surfaces which significantly increases the thermal background and decreases the optical throughput of the system (Lloyd-Hart 2000). However, the MMT utilizes a completely new type of 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 possibility of thermal IR AO imaging (Close et al. 2003b; Biller et al. 2003) becomes a reality.

The DM consists of 336 voice coil actuators that push on 336 small magnets glued to the backsurface of a thin (2.0 mm thick) 642 mm aspheric ULE glass "shell" (for a detailed review of the secondary mirror see (Brusa et al. 2003a; Brusa et al. 2003b)). We have complete positional control of the surface of this reflective shell by use of a capacitive sensor feedback loop. This positional feedback loop allows one to position an actuator of the shell to within 4 nm rms (total surface errors amount to only 40 nm rms over the whole secondary). The AO system samples at 550 Hz using 108 active subapertures. For a detailed review of the MMT AO system see Wildi et al. (2003a,b) and references within.

2.2. *MMT AO Observations*

During our second engineering run we observed the θ^1 Ori B group on the night of Jan 20, 2003 (UT). The AO system corrected the lowest 52 system modes and was updated at 550 Hz. The closed loop bandwidth was estimated at 30 Hz 0 dB. Without AO correction our images had FWHM=$0.6''$, after AO correction our 23 second images had improved to FWHM=$0.070''$ (close to the diffraction limit of $0.056''$ in the H-band). A detailed analysis suggested that during our engineering run a 40 Hz vibration in the MMT telescope increased our FWHM by $\sim 0.015''$ and decreased our Strehl by a factor of two. We are in the process of identifying and decreasing the effect of this 40 Hz vibration. In any case, as Figure 1 clearly shows, there is a large improvement in image quality (the Strehl increases by 20 times) with the adaptive secondary AO system.

2.2.1. *The Indigo Near-IR Video Camera*

Since these observations were carried out during the engineering run we utilized a commercially available 320x256 InGaAs 0.9-1.68 μm "Merlin-NIR" video camera. Although this commercial camera (produced by the Indigo company) is not nearly as sensitive as our facility AO camera (AIRES; McCarthy et al. (1998)) it still provides excellent dynamical information about the performance of the AO system on bright objects (it will be replaced by the ARIES camera in the fall of 2003). Here we use it as a simple NIR (H band) science camera.

The Indigo camera was fed by a relay lens that converted the f/15 AO corrected beam to a f/39 beam yielding $0.0242 \pm 0.0020''$ per $30\mu m$ pixel (providing a $7.7 \times 6.2''$ FOV). Astrometric standards ADS 8939 and ADS 7158 were observed to calibrate this platescale and error (see Figures 2 & 3). It was found that the direction of north was slightly (0.113°) east of Indigo's Y axis (when the parallactic angle was zero (transit) and one is looking towards the south). During this commissioning run we did not observe with the MMT Cassegrain derotator tracking field rotation, hence all images must be rotated by the appropriate parallactic angle (plus 0.113°) to have north up and east to the left on the Indigo camera.

The camera was mounted under a high optical quality dichroic which sent the visible light (0.5-1 μm) to the 108 subaperture shack-Hartmann wavefront sensor (WFS). The infrared light ($\lambda > 1\mu m$) was transmitted to the Indigo camera. The camera had a standard H band filter (1.6μm) mounted 3 inches from focus in a light-tight barrel.

To maximize the sensitivity of the Indigo camera we carried out a standard "2-point" calibration on a both a dark (cold) flat field source and on a bright (hot) source to scale the automatic gain control/dynamic range of the camera's electronics. This appeared to yield images that were auto flat fielded to a few percent in accuracy when the counts were between the linear range defined by the dark and bright calibration flats. The camera was remotely controlled via a serial port. Digital (16 bit) data were streamed to the control PC's hard drive. Data could be acquired as fast as 50 frames per second (although data in this paper was acquired at 15 frames/sec to sample longer periods on the sky). Integration times can range from 1-16000 μs. The lack of a longer integration time (since the camera is primarily intended for commercial high-background, high-bandwidth applications) leads to most sources being read-noise limited. However, we found that point sources of $H \sim 11$ could be detected in 3 s of total exposure (200 16 ms frames) with AO correction at the MMT. Although insensitive by most astronomical standards the Indigo camera is able to capture temporal events of durations as short as 1 μs. In this paper we will focus on the ability of the Indigo camera to produce high resolution (0.07″) images of the θ^1 Ori B group.

2.2.2. *Reducing the Indigo MMT AO Data*

For the θ^1 Ori B group we obtained 7 series of 200x16 ms data cubes with the Indigo camera. The data from each cube was simply averaged together to produce 7 individual 3.2 second exposures. A similarly reduced cube of "sky" images was subtracted from each data set. These 7 sky-subtracted exposures were then rotated (in IRAF) by the current parallactic angle (plus the 0.113° offset) so north was aligned with the Y axis, and east is the negative X axis. Then each of the 7 images were cross-correlated and aligned with a cubic spline interpolator. Then the final stack of images were median combined to produce the final image. The final image is displayed in Figure 4.

2.3. *Hokupa'a/Gemini Images of the Trapezium*

In addition to our excellent MMT images of the θ^1 Ori B group we also have an epoch of K' images of the central 30″ of the cluster. These Hokupa'a/Gemini (Graves et al. 1998; Close et al. 1998) AO images were taken September 19, 2001. We acquired a series of 10 short (1 s) images and dithered the telescope in a 10x10″ box while AO guiding off θ^1 Ori B itself (as in the case of the MMT AO observations). We utilized the QUIRC IR camera (Hodapp et al. 1996) with a calibrated platescale of $0.0199 \pm 0.0002''$/pix (Potter et al. 2002a).

2.3.1. *Reducing the Gemini data*

We have developed an AO data reduction pipeline in the IRAF language which maximizes sensitivity and image resolution. This pipeline is standard IR AO data reduction and is described in detail in Close et al. (2002a,b).

The pipeline cross-correlates and aligns each image, then rotates each image so north is up (to an accuracy of ±0.3 degrees) and east is to the left, then median combines the data with an average sigma clip rejection at the $\pm 2.5\sigma$ level. By use of a cubic-spline interpolator the script preserves image resolution to the < 0.02 pixel level. Next the custom IRAF script produces two final output images, one that combines all the images taken (see Figure 5) and another where only the sharpest 50% of the images are combined (this high-Strehl image was very similar to that shown in Figure 5, just a bit noisier – and so was not further analyzed).

The final image (see Figures 5 and 6) has FWHM=0.085″ which is just slightly worse than the MMT data. Even though Gemini is a larger telescope (8.2-m), Hokupa'a's fitting error (36 elements over 50 meters^2) is worse than that of the MMT (52 modes over 33 meters^2), hence higher resolution images can result from the smaller of the two telescopes (Gemini has a diffraction-limit of 0.056″ at K' similar to that of the MMT at H). However, Hokupa'a's curvature WFS could guide on much fainter (R∼ 17) guide stars (Close et al. 2002a,b; Siegler, Close, & Freed 2002).

3. REDUCTIONS

In Table 1 we present the analysis of our MMT and Gemini images in Figures 4 and 5. The photometry was based on DAOPHOT's PSF fitting photometry task ALLSTARS (Stetson 1987). The PSF used was θ^1 Ori B_1 itself. Since all the members of the θ^1 Ori B group are located within 1″ of θ^1 Ori B_1 the PSF fit is excellent (there is no detectable change in PSF morphology due to anisoplanatic effects inside the θ^1 Ori B group (Diolaiti et al. 2000)).

Since the PSF model was so accurate and the data had such high signal to noise (and high resolution) it was possible for DAOPHOT to measure relative positions to within 0.003″. We estimate this error based on the scatter of the θ^1 Ori B_1B_2 separation (which should be very close to a constant since the B_1B_2 system has an orbital period of ∼ 2000 yr). The lack of any motion between B_1 and B_2 is also confirmed by Schertl et al. (2003). Our data is summarized in Table 1. Linear (weighted) fits to the data in Table 1 (Figures 7 to 12) yield the velocities shown in Table 1. The overall error in the relative proper motions observed is $\sim 0.002''$/yr in proper motion (∼ 4 km/s).

4. ANALYSIS

With these accuracies it is now possible to determine whether these stars in the θ^1 Ori B group are bound together, or merely chance projections in this very crowded region. As can be seen from Table 1 and Figures 7 – 12 there is very little relative motion between any of the members of the θ^1 Ori B group. Therefore it is possible that the group is physically bound together.

If we adopt the masses of each star from the Siess Forestini & Dougados (1997); Bernasconi & Maeder (1996) tracks fit by Weigelt et al. (1999) we find masses of: $B_1 \sim 7M_\odot$; $B_2 \sim 3M_\odot$; $B_3 \sim 2.5M_\odot$; $B_4 \sim 0.2M_\odot$; $B_5 \sim 7M_\odot$; $A_1 \sim 20M_\odot$; $A_2 \sim 4M_\odot$; and $A_3 \sim 2.6M_\odot$. 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 yields an error in the proper motions of only $\sim 0.002''$/yr according to the scatter in the B_1B_2 and B_1B_3 systems (see Table 1). We have observed orbital motion in the very tight θ^1 Ori B_2B_3 (see Figure 10) and θ^1 Ori A_1A_2 (see Figure 12) systems, with 52 and 94 AU separations; respectively.

4.1. *Is the θ^1 Ori B_2B_3 System Physical?*

The relative velocity in the θ^1 Ori B_2B_3 system (in the plane of the sky) is $\sim 4.2 \pm 2.1$ km/s (mainly in the azimuthal direction; see Figure 10). This is a reasonable V_{tan} since an orbital velocity of ~ 6.7 km/s is expected from a face-on circular orbit from a $\sim 5.5M_\odot$ binary system like θ^1 Ori B_2B_3 with a 52 AU projected separation. It is worth noting that this velocity is also greater than the ~ 3 km/s Hillenbrand & Hartmann (1998) dispersion velocity of the cluster. Hence it is most likely that these two $K' = 7.6$ and $K' = 8.6$ stars (separated by just $0.116''$) are indeed in orbit around each other. Moreover, there are only 10 stars known to have $K' < 8.6$ in the inner $30 \times 30''$ (see Figure 6), we can estimate that the chances of finding two bright ($K' < 8.6$) stars within $0.116''$ is a small $< 10^{-4}$ probability.

Our observed velocity of $0.93 \pm 0.49°$/yr is consistent (in both direction and magnitude) with the $1.4°$/yr observed by Schertl et al. (2003). This suggests that the AO and speckle datasets are both detecting real motion. Moreover, since this motion is primarily azimuthal strongly suggests an orbital arc of B_3 orbiting B_2.

4.2. *Is the θ^1 Ori A_1A_2 System Physical?*

We observe $\sim 16.5 \pm 5.7$ km/s of relative motion in the θ^1 Ori A_1A_2 system (mainly in the azimuthal direction; see Figure 12). This is higher than the average dispersion velocity of ~ 3 km/s but still close to an estimated periastron velocity of the $\sim 20M_\odot$ A_1A_2 system (projected separation of 94 AU). Hence it is highly likely that these two $K' = 6.0$ and $K' = 7.6$ stars (separated by just $0.21''$) are indeed in orbit around each other. In addition, there are only 8 stars known to have $K' < 7.6$ in the inner $30 \times 30''$ (see Figure 6), we can estimate that the chances of finding two bright ($K' < 8.6$) stars within $0.21''$ is a small $< 4 \times 10^{-4}$ probability.

Our observed velocity of 16.5 ± 5.7 km/s is consistent (in both direction and magnitude) with the ~ 10.3 km/s observed by Schertl et al. (2003). This again suggests that the AO and speckle datasets are both detecting real motion of A_2 orbiting A_1.

4.3. *Is the θ^1 Ori B Group Stable?*

The pair B_1B_5 is moving at $\sim 1.4 \pm 4.4$ km/s in the plane of the sky w.r.t. to the pair B_2B_3 where the escape velocity $V_{esc} \sim 6$ km/s for this system. Hence these pairs are very likely gravitationally bound together. However, radial velocity measurements will be required to be absolutely sure that these 2 pairs are bound together.

4.3.1. *Is the Orbit of θ^1 Ori B_4 Stable?*

The situation is somewhat different for the faintest component of the group, B_4. It has $K = 11.66$ mag which according to Hillenbrand & Carpenter (2000) suggests a mass of only $\sim 0.2\,M_\odot$. Since there are only 20 stars known to have $K < 11.66$ in the inner $30''$ (see Fig. 6), we can estimate that the chances of finding a $K < 11.66$ star within $0.6''$ of B_1 is a small $< 8 \times 10^{-3}$ probability. Our two AO measurements (and the one speckle detection of Schertl et al. (2003)) did not detect a significant velocity of B_4 w.r.t. B_1 (4 ± 15 km/s; see Figures 13 & 14). Together with the escape velocity of ~ 6 km/s, this points towards B_4 being also a gravitationally bound member of the θ^1 Ori B group.

On the other hand, its mass and its location w.r.t. to the other four groups members makes it highly unlikely that B_4 is on a stable orbit within the group. To reconcile these conflicting observations, one may think of *(a)* B_4's projected distances from the other B group members being considerably smaller than the true distance thus making a stable orbit much more likely, or *(b)* B_4's current motion pointing almost exactly along our line of sight, allowing for a higher true velocity, or *(c)* B_4 being a chance projection of an object not related to the other four members of the B group. Without additional astrometric data, we cannot yet decide which of these three possibilities is the most likely.

4.3.2. *Is the orbit of B_3 around B_2 and of B_5 around B_1 stable longterm?*

B_1B_5, and B_2B_3 are two binaries with projected separations of 0.13 AU (B_1B_5) and 52 AU (B_2B_3); respectively. The two pairs are separated by a projected distance of 415 AU. The distance $D_{B_1B_5} \sim 3 \times 10^{-4} \times D_{B_1B_5B_2B_3}$ and thus the B_1B_5 system is stable. Much more interesting is the case of B_2B_3. Their projected distance is not very small compared to their projected distance (D) from the B_1B_5 pair:$D_{B_2B_3} \sim 0.12 \times D_{B_1B_5B_2B_3}$. Thus the stability of the B_2B_3 orbit needs a more detailed analysis since it is possible that B_3 may be ejected in the future.

Eggelton & Kiseleva (1995) have given an empirical criterion for the long-term stability of the orbits of hierarchical triple systems, based on the results of their extensive model calculations (Kiseleva & Eggelton 1994; Kiseleva et al. 1994; Eggelton & Kiseleva 1995). Their analytic stability criterion is good to about $\pm 20\%$, and is meant to indicate stability for another 10^2 orbits. Given the uncertainties of the masses of the members of the B group, this accuracy is sufficient for our present discussion.

The orbital period of the two binaries w.r.t. each other is $P_{(15)/(23)} \sim 1920$ yrs, while the orbital period of B_3 w.r.t B_2 amounts to $P_{2/3} \sim 160$ yrs. For the calculation of both periods, we have assumed the masses as given above, and circular orbits in the plane of the sky. This leads to a period ratio $X = P_{(15)/(23)}/P_{2/3} \sim 12$. Eggelton & Kiseleva's stability criterion requires $X \geq X_{crit} = 10.08$ for the masses in the B group. This means that within the accuracy limits of our investigation, the binary B_2B_3 is just at the limit of stability. The stability criterion depends also on the orbits' eccentricities. In our case, already mild eccentricities of the order of $e \sim 0.1$ (as can be expected to develop in hierarchical triple systems; see, e.g., Georgakarakos 2002), make the B group unstable. While we cannot decide yet whether the pair B_2B_3 orbit each other in a stable way, it is safe to say that that the "triple" B_1B_5, B_2, and B_3 is not a simple, stable hierarchical triple system.

The θ^1 Ori B system seems to be a good example of a highly dynamic star formation "mini-cluster" which is possibly in the process of ejecting the lowest-mass member through dynamical decay (Durisen, Sterzik, & Pickett 2001), and breaking up the gravitational binding of the widest of the close binaries (the B_2B_3 system). The "ejection" of the lowest-mass member of a formation "mini-cluster" could play a major role in the formation of low mass stars and brown dwarfs (Reid et al. 2001a; Bate et al. 2002; Durisen, Sterzik, & Pickett 2001; Close et al. 2003a). The breaking up of binaries, of course, modifies the binary fraction of main sequence stars considerably as well.

5. FUTURE OBSERVATIONS

In our opinion it is most likely that these θ^1 Ori A & B group stars are bound. We caution, however, that the motion of each of these stars could currently be fit equally well by linear motion (not orbital arcs). Future high resolution observations are required to see if these stars follow true orbital arcs around each other proving that they are interacting. In particular, future observations of the θ^1 Ori B_4 positions would help reduce the scatter in the velocity data and indicate if it is indeed part of the θ^1 Ori B group.

Future observations should also try to determine the radial velocities of these stars. Once radial velocities are known one can calculate unambiguously if these systems are bound. Such observations will require both very high spatial and spectral resolutions. This might be possible with such future instruments like the future AO fed ARIES instrument.

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Table 1
High Resolution Observations of the θ^1 Ori B & A groups

System name	ΔH (mag)	$\Delta K'$ (mag)	Separation ($''$)	Separation Vel. (Sep. $''$/yr)	PA ($^\circ$)	PA Velocity ($^\circ$/yr)	Telescope	epoch (m/d/y)
B_1B_2	2.30 ± 0.15		$0.942 \pm 0.020''$		254.9 ± 1.0		SAO[a]	10/14/97
		1.31 ± 0.10[b]	$0.942 \pm 0.020''$		254.4 ± 1.0		SAO[a]	11/03/98
		2.07 ± 0.05	$0.9388 \pm 0.0040''$		255.1 ± 1.0		GEMINI	09/19/01
	2.24 ± 0.05		$0.9375 \pm 0.0030''$		255.1 ± 1.0		MMT	01/20/03
				-0.0006$\pm$0.0019$''$/yr		0.07$\pm$0.25°/yr		
B_2B_3	1.00 ± 0.11		$0.114 \pm 0.05''$		204.3 ± 4.0		SAO[a]	10/14/97
		1.24 ± 0.20	$0.117 \pm 0.005''$		205.7 ± 4.0		SAO[a]	11/03/98
		1.04 ± 0.05	$0.1166 \pm 0.0040''$		207.8 ± 1.0		GEMINI	09/19/01
	0.85 ± 0.05		$0.1182 \pm 0.0030''$		209.7 ± 1.0		MMT	01/20/03
				$0.0006 \pm 0.0010''$/yr		0.93$\pm$0.49°/yr		
B_1B_4		5.05 ± 0.8	$0.609 \pm 0.008''$		298.0 ± 2.0		SAO[c]	02/07/01
		5.01 ± 0.10	$0.6126 \pm 0.0040''$		298.2 ± 1.0		GEMINI	09/19/01
	4.98 ± 0.10		$0.6090 \pm 0.0050''$		298.4 ± 1.0		MMT	01/20/03
				$-0.0017 \pm 0.0033''$/yr		0.18$\pm$0.95°/yr		
A_1A_2	1.51 ± 0.15	1.38 ± 0.10	$0.208 \pm 0.030''$		343.5 ± 5.0		Calar Alto[d]	11/15/94
		1.51 ± 0.05	$0.2215 \pm 0.005''$		353.8 ± 2.0		SAO[a]	11/03/98
		1.62 ± 0.05	$0.2051 \pm 0.0030''$		356.9 ± 1.0		GEMINI	09/19/01
				$-0.0064 \pm 0.0027''$/yr		2.13$\pm$0.73°/yr		

[a]speckle observations of Weigelt et al. (1999).

[b]these low ΔK values are possibly due to θ^1 Ori B_1 being in eclipse during the 11/03/98 observations of Weigelt et al. (1999).

[c]speckle observations of Schertl et al. (2003).

[d]speckle observations of Petr et al. (1998).

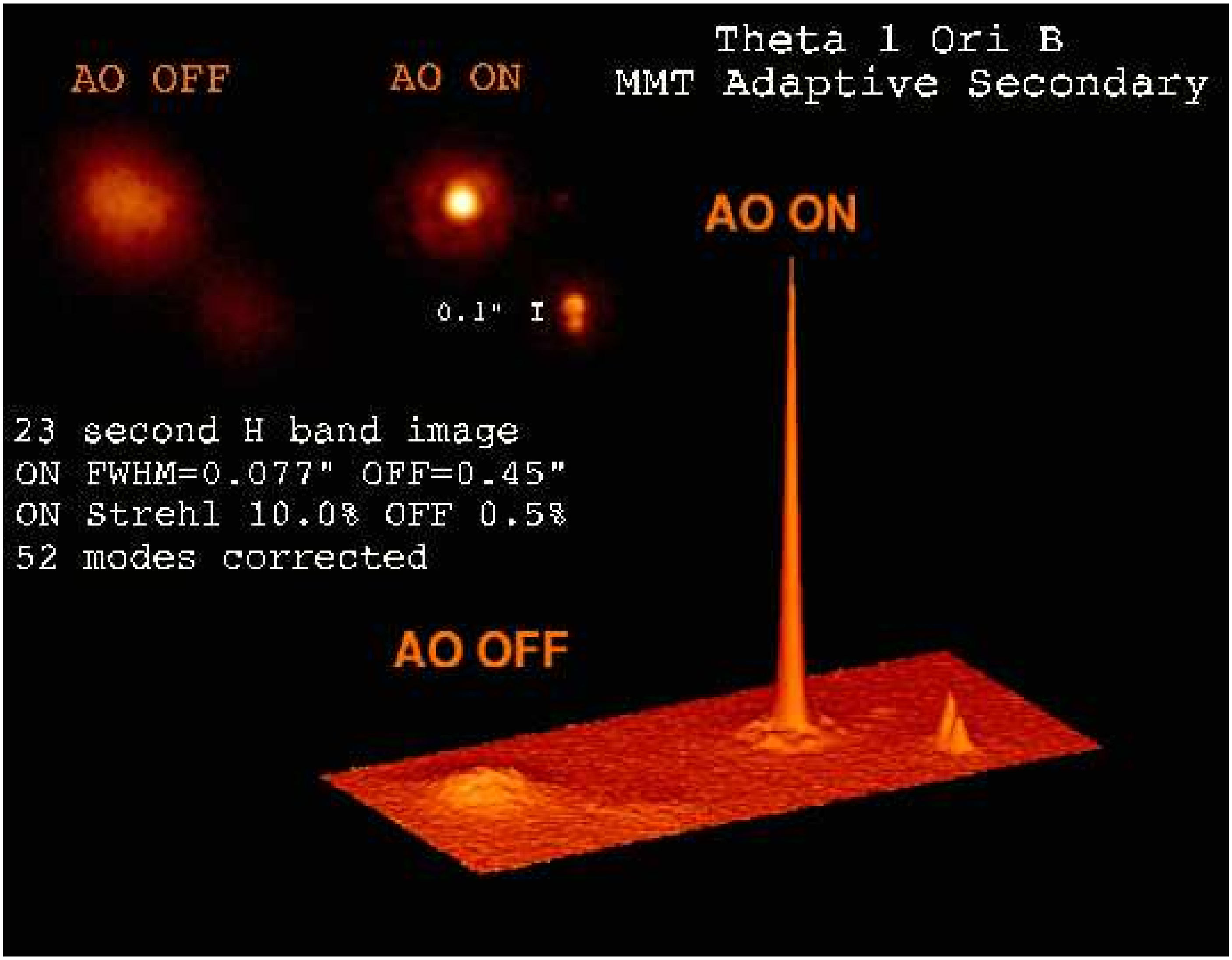

FIG. 1.— A typical example of how the the Adaptive Optics (AO) system can make very sharp images. With AO "OFF" θ^1 Ori B appears to be just 2 stars. With AO turned "ON" it is clearly a tight group of 4 visual stars. Note how with AO correction the peak intensity increases by 20 times and the resolution becomes ten times better.

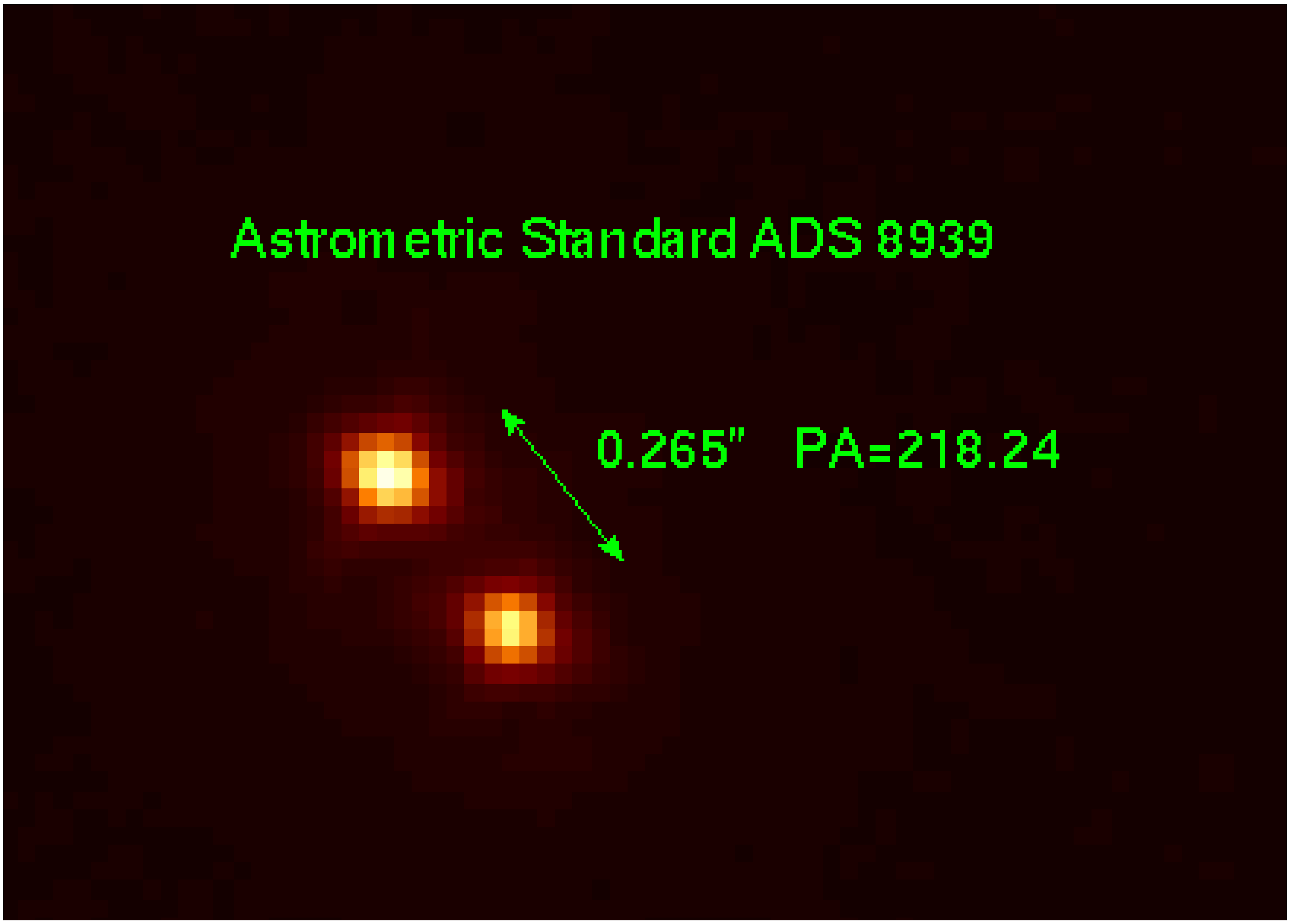

Fig. 2.— An H band MMT AO image of the astrometric binary ADS 8939 (WDS 13329+3454; STT 269AB). The well known orbit (WDS Grade level 2) of this binary star predicted a separation of 0.265″ and a PA of 218.237° for UT Jan 19, 2003 (the night of this observation). For these values we derived that the Indigo camera had a platescale of 0.0242″/pixel. This 10 second integration had a mid-point time of UT 12:21:30, hence the parallactic angle during this exposure was −107.6°. Rotating the image by −107.6° (clockwise) resulted in a measured PA of 218.35° which indicates North is 0.113° east of the Indigo's Y axis. Linear color scale. North is up and east is left.

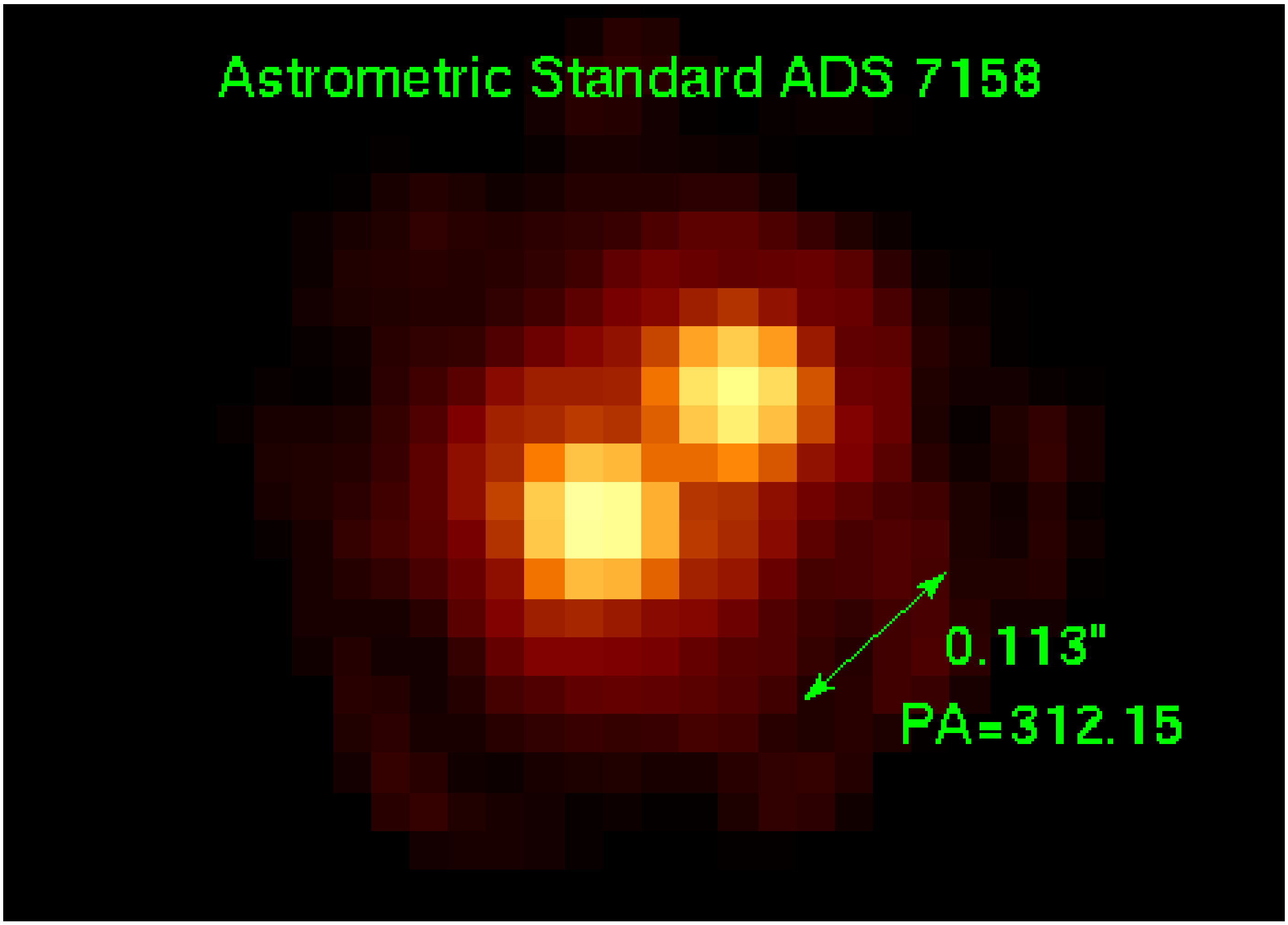

Fig. 3.— An H band image of the astrometric binary ADS 7158 (WDS 09036+4709; A 1585). The well known orbit (WDS Grade level 2) of this binary star predicted a separation of 0.111″ and a PA of 312.764° for UT Jan 20, 2003 (the night of this observation). We utilized these values to check the 0.0242″/pixel platescale and orientation (north being 0.113° east of the Indigo's Y axis) that were obtained from the ADS 8939 observations for the Indigo camera (see Figure 2). The above 10 second integration had a mid point time of UT 8:18:50, hence the parallactic angle during this exposure was −171.0°. Rotating the image by −171.0° (and correcting for the 0.113° misalignment of the Y axis) resulted in a measured PA of 312.146° which which is incorrect by 0.62°. Hence we conservatively estimate our PA is calibrated to with ±1°. The separation of ADS 7158 is 4.677 pixels suggesting a platescale of 0.0241″/pixel. Hence we estimate a conservative ±0.002″ error in the Indigo platescale of 0.0242″/pixel. Logarithmic color scale, note the Airy rings around each component. North is up and east is left.

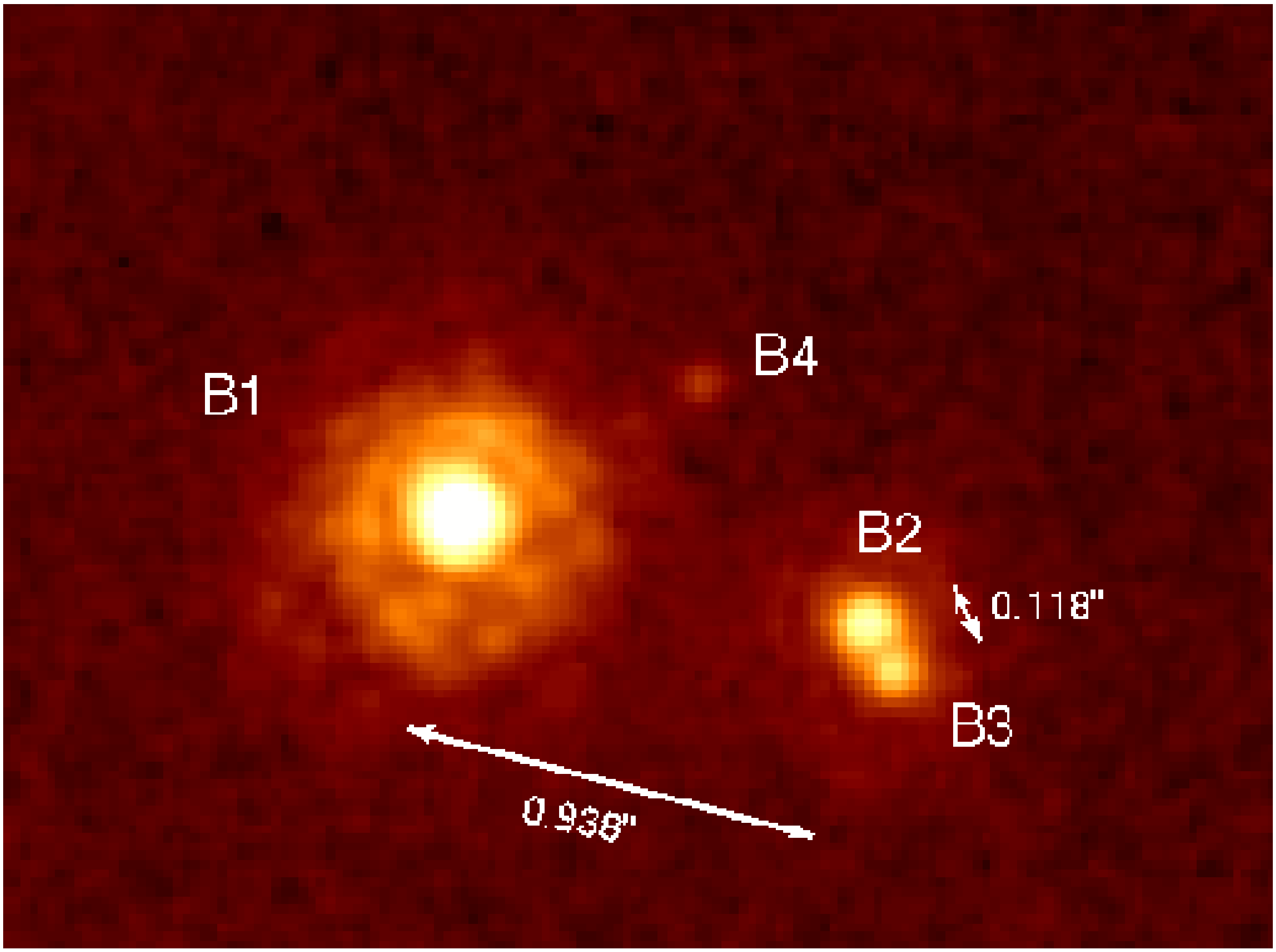

Fig. 4.— Detail of the θ^1 Ori B group as imaged at 0.077″ resolution (in the H band) with the MMT AO system and the Indigo IR camera. Logarithmic color scale. North is up and east is left. Note that the object "B_1" is really an eclipsing spectroscopic binary (B_1B_5); where the unseen companion B_5 orbits B_1 every 6.47 days (Abt, Wang, & Cardona 1991).

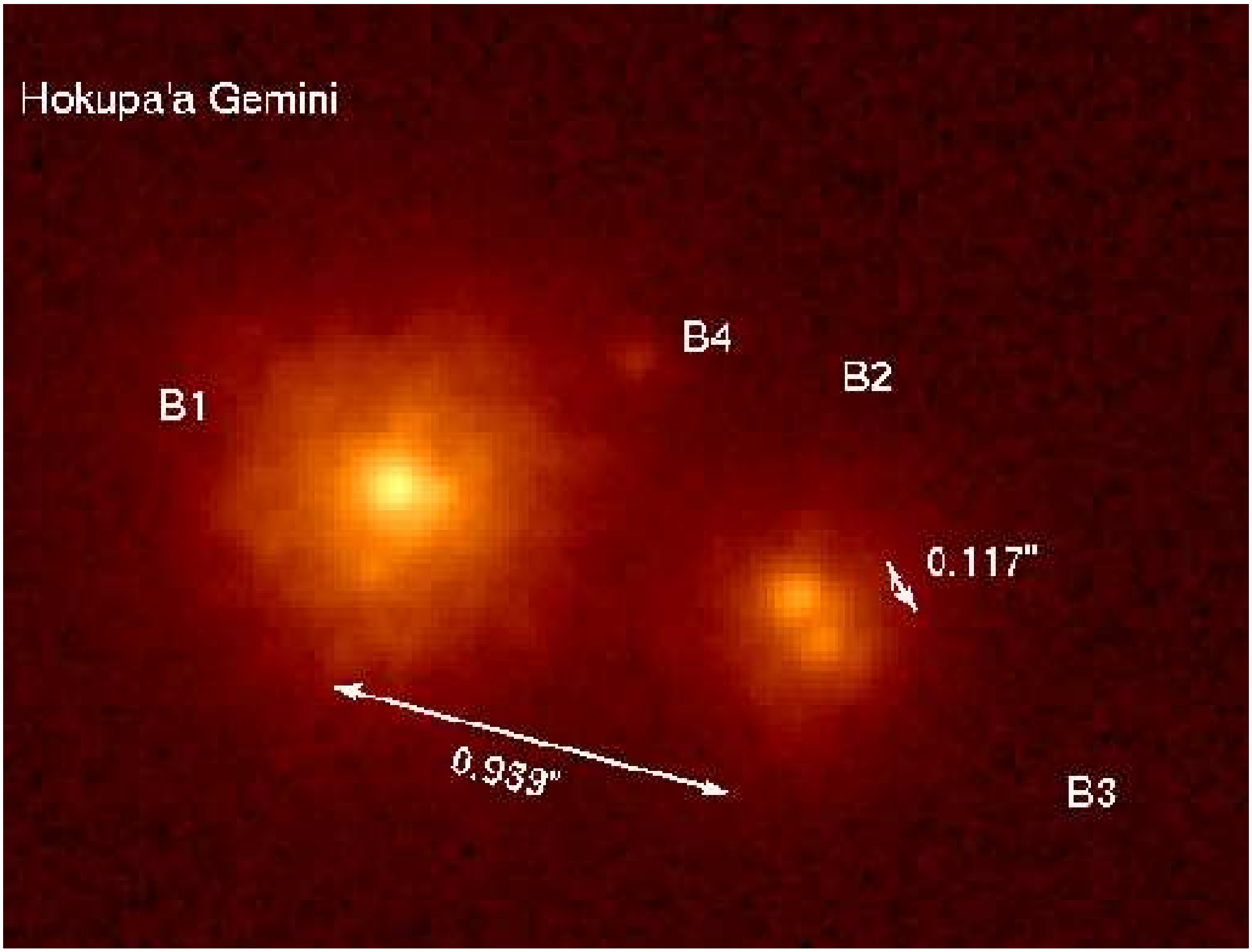

FIG. 5.— The Gemini/Hokupa'a images of the θ^1 Ori B group in the K' band. Resolution 0.085″. Logarithmic color scale. North is up and east is left.

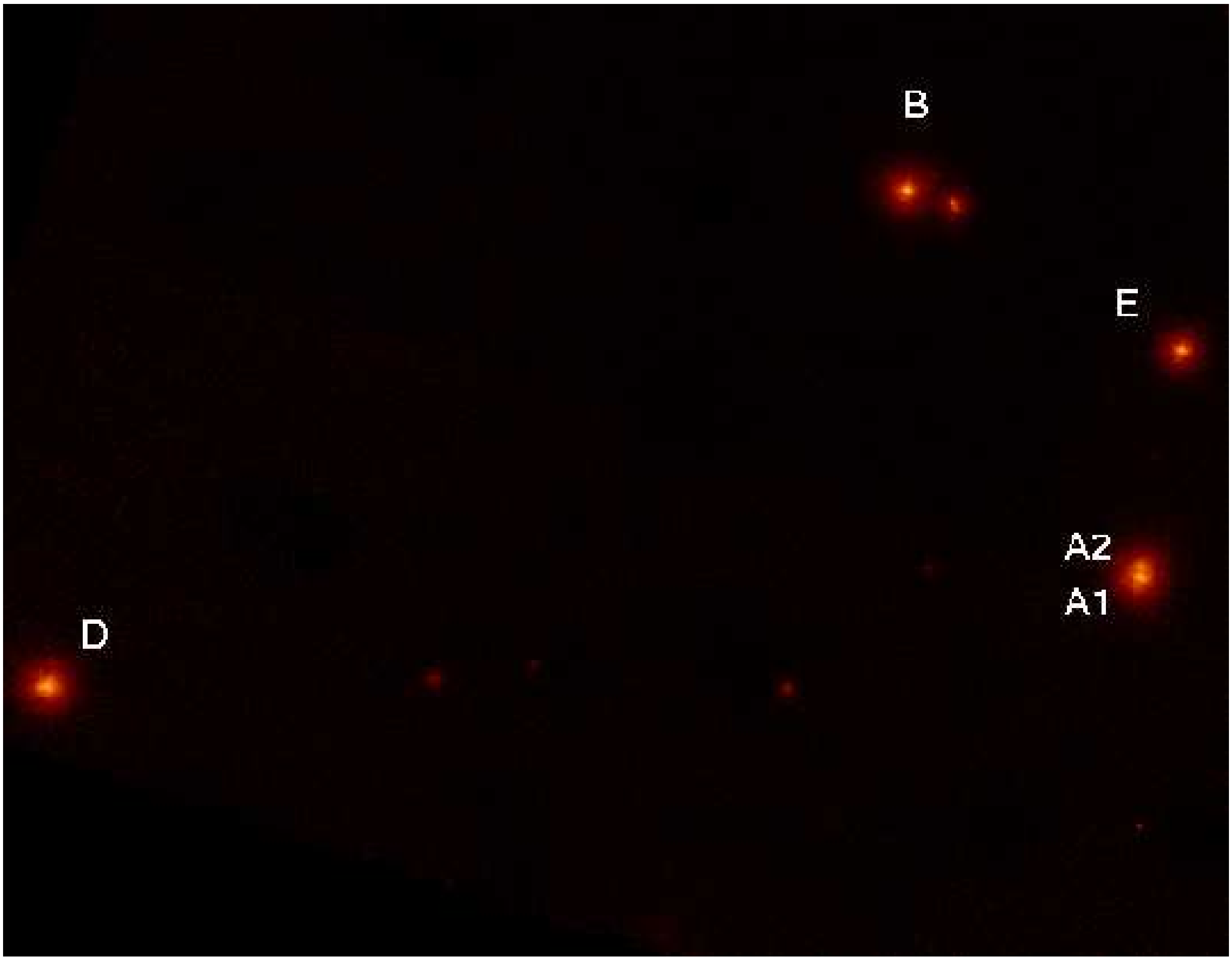

Fig. 6.— The upper part of the θ^1 Ori cluster as imaged over $30 \times 30''$ FOV at Gemini with the Hokupa'a AO system. Logarithmic color scale. North is up and east is left. Note that the object "A_1" is really a spectroscopic binary ($A_1 A_3$); where the unseen companion A_3 is separated from A_1 by 1 AU (Bossi et al. 1989)

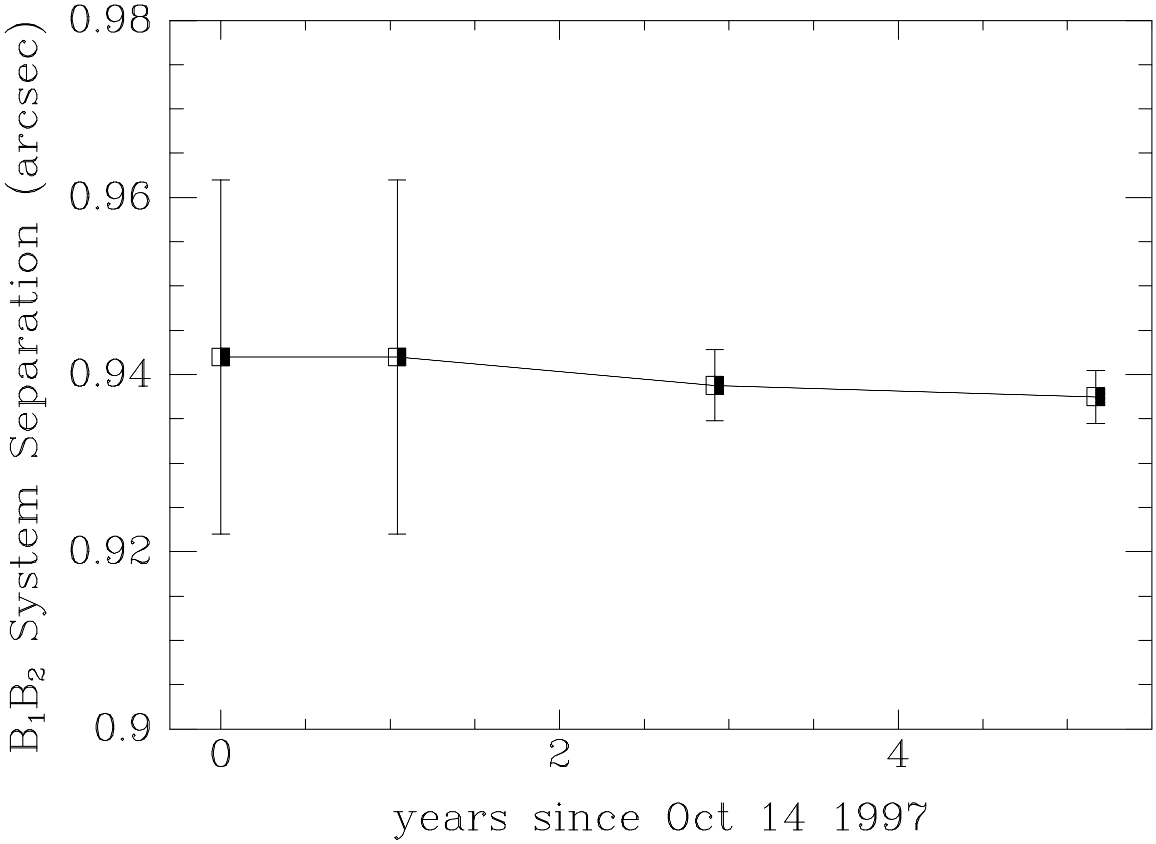

FIG. 7.— The separation between θ^1 Ori B_1 and B_2. Note how over five years of observation there has been little significant relative proper motion observed (-0.0006±0.0019″/yr; which is insignificantly different from a constant). If the group is gravitationally bound the separation should be roughly constant over five years. The observed rms scatter from a constant value is indeed a mere ±0.0019″, suggesting the whole θ^1 Ori B group is likely physically bound together. The first 2 data points are speckle observations from the 6-m SAO telescope (Weigelt et al. 1999), the next point is from our Gemini/Hokupa'a observations and the last data point is from the MMT AO observations.

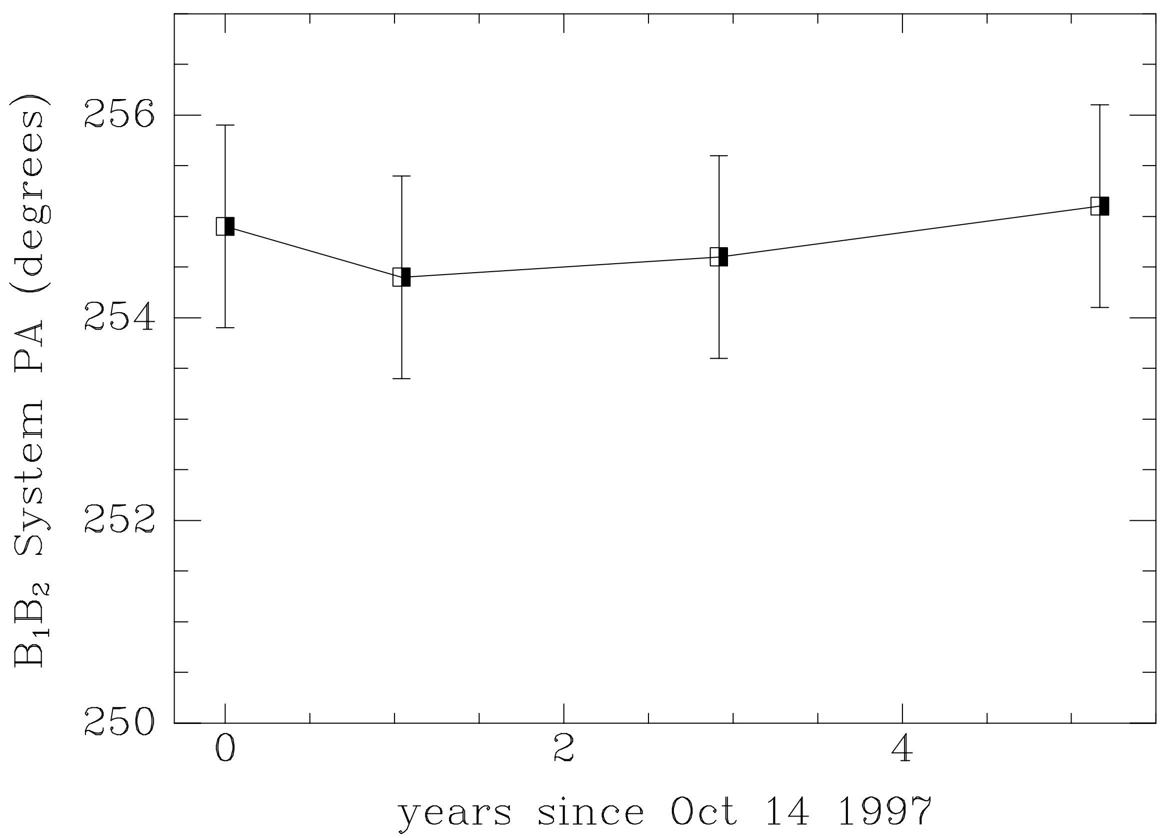

FIG. 8.— The position angle between θ^1 Ori B_1 and B_2. Note how over five years of observation there has been no significant relative proper motion observed ($0.07\pm0.25°$/yr which is insignificantly different from a constant). The error from a constant value is a mere $\pm0.3°$.The first 2 data points are speckle observations from the 6-m SAO telescope (Weigelt et al. 1999), the next point is from our Gemini/Hokupa'a observations and the last data point is from the MMT AO observations.

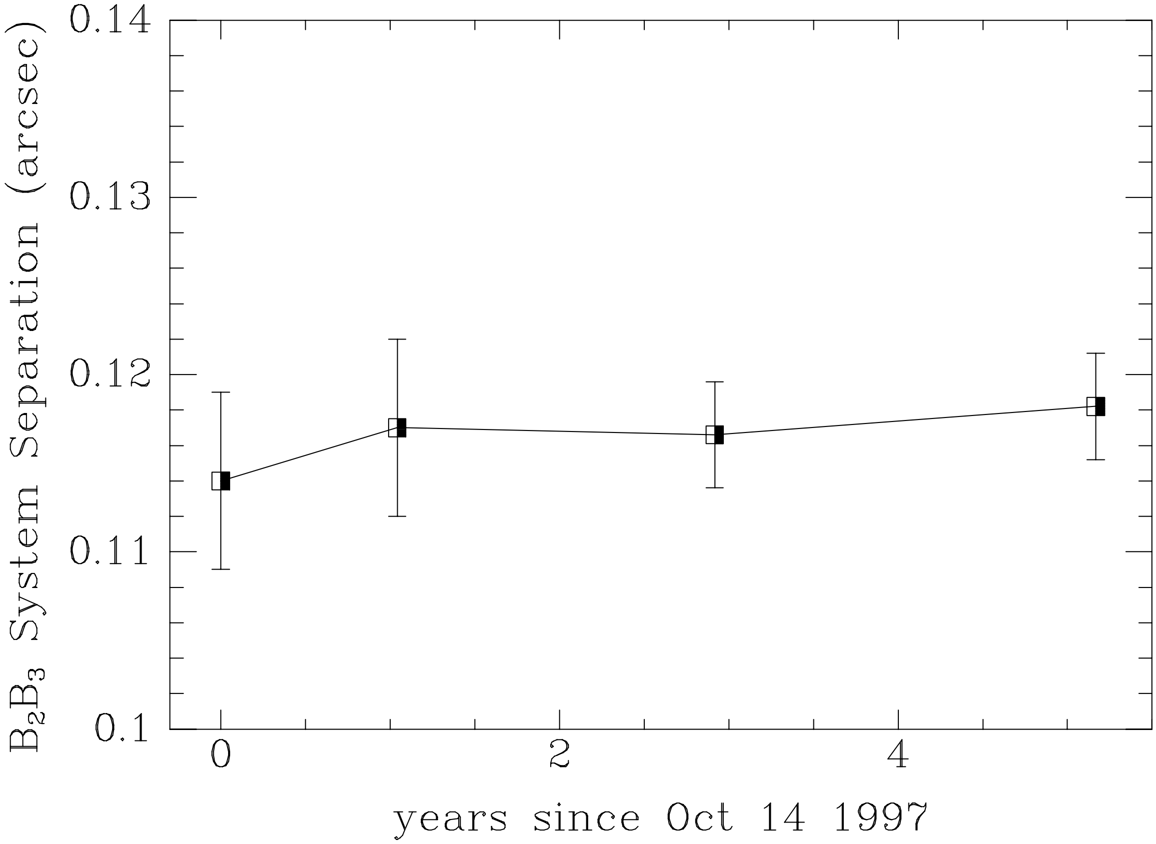

FIG. 9.— The separation between θ^1 Ori B_2 and B_3. Note the lack of any significant relative motion ($0.0006 \pm 0.0010''$/yr). The rms scatter from a constant value is only $0.001''$. There appears to very little change in the separation of the B_2B_3 system. The first 2 data points are speckle observations from the 6-m SAO telescope (Weigelt et al. 1999), the next point is from our Gemini/Hokupa'a observations and the last data point is from the MMT AO observations.

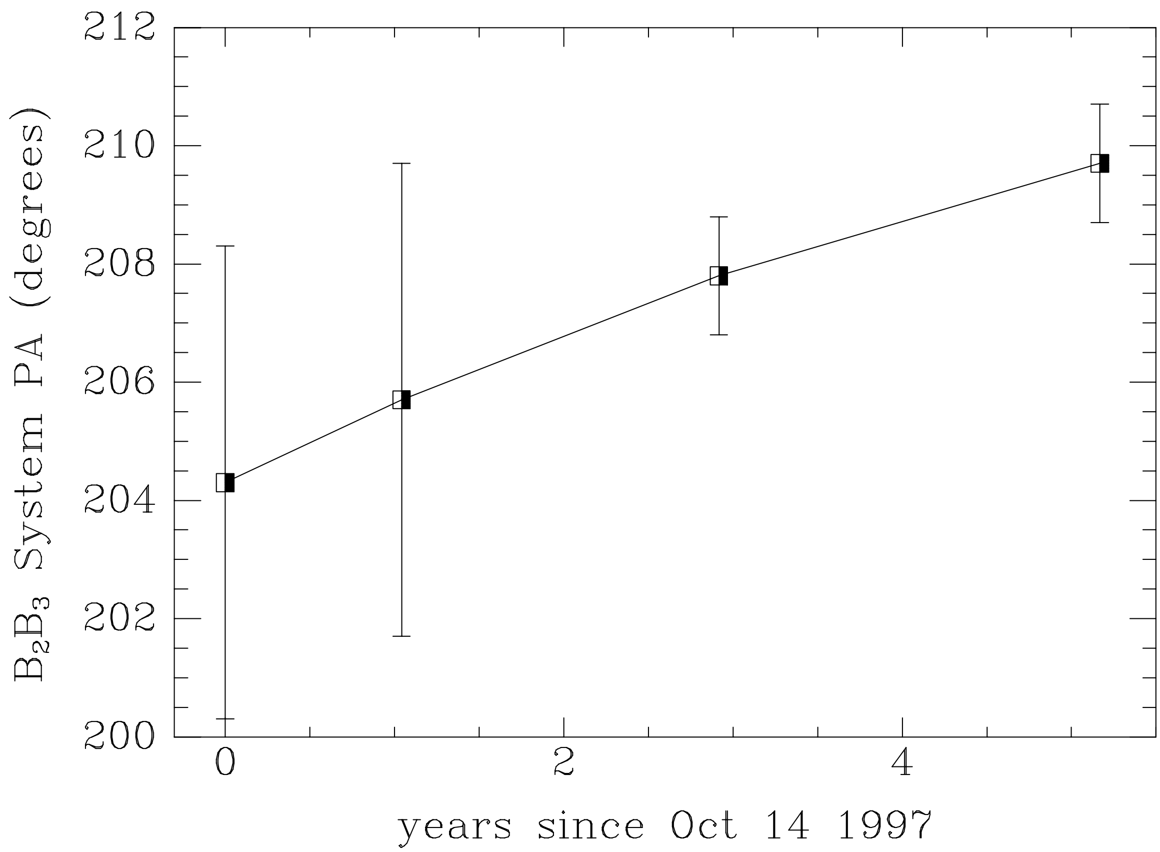

Fig. 10.— The position angle of θ^1 Ori B_2 and B_3. Here we observe what may be real orbital motion of B_3 moving counter-clockwise (at $0.93\pm0.49°$/yr; correlation significant at the 99.2% level) around B_2. This small amount of motion is consistant with the B_2B_3 system being bound. The first 2 data points are speckle observations from the 6-m SAO telescope (Weigelt et al. 1999), the next point is from our Gemini/Hokupa'a observations and the last data point is from the MMT AO observations.

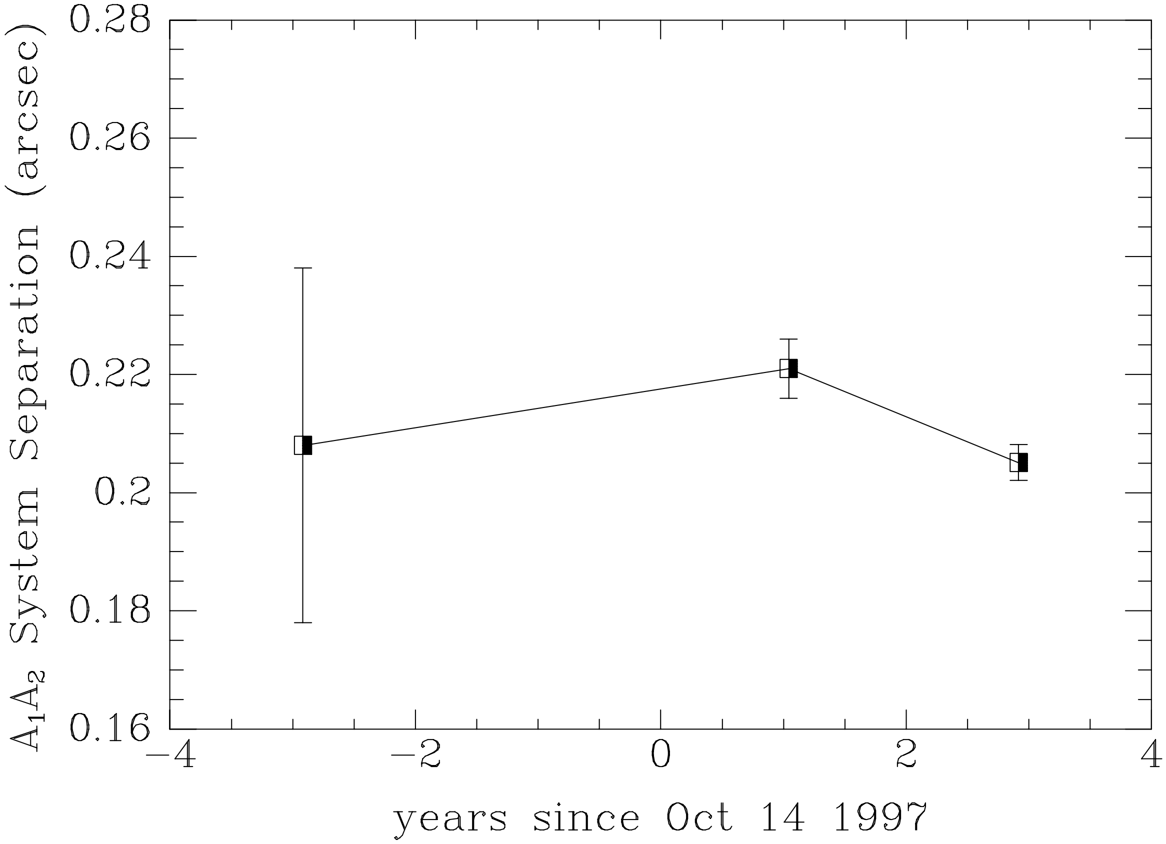

FIG. 11.— The separation between θ^1 Ori A_1 and A_2. There is a small negative changes in the orbital separation ($-0.0064 \pm 0.0027''$/yr) as A_2 moves towards A_1. The first data point is from speckle observations at the 3.5-m Calar Alto telescope (Petr et al. 1998), the next point is from a speckle observation from the 6-m SAO telescope (Weigelt et al. 1999), the last point is from our Gemini/Hokupa'a observations.

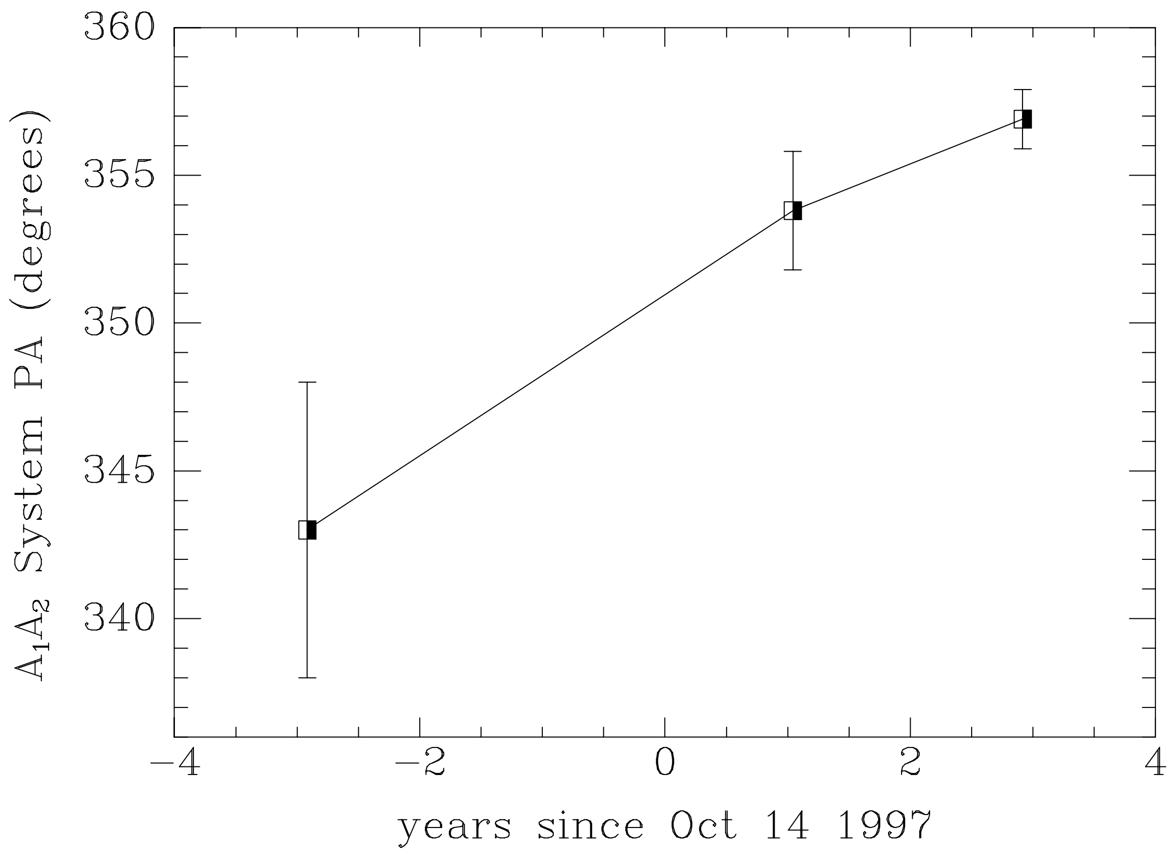

FIG. 12.— The position angle of θ^1 Ori A_1 and A_2. There does appear to be significant changes in the position angle as A_2 moves counter clockwise (at 2.13±0.73°/yr) around A_1. This relatively small motion is consistent with the A_1A_2 system being bound. The first data point is from speckle observations at the 3.5-m Calar Alto telescope (Petr et al. 1998), the next point is from a speckle observation from the 6-m SAO telescope (Weigelt et al. 1999), the last point is from our Gemini/Hokupa'a observations.

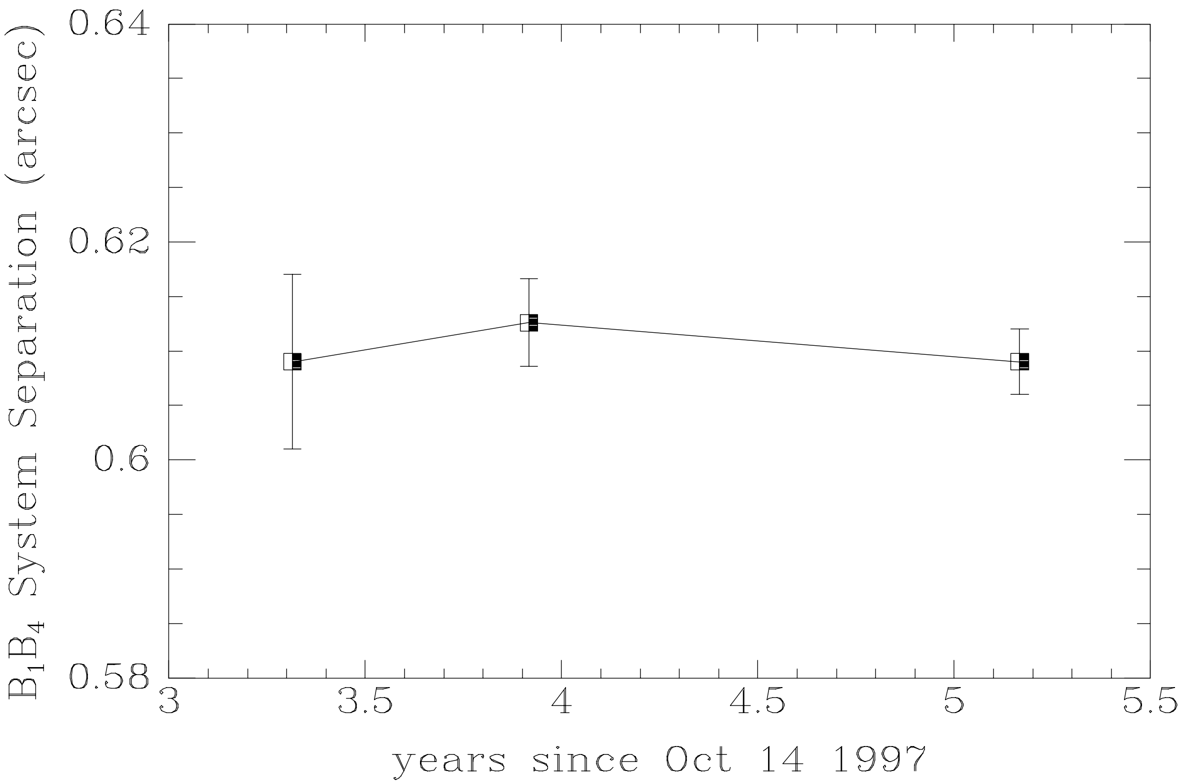

FIG. 13.— The separation between θ^1 Ori B_1 and B_4. Note how over three years of observation there has been little significant relative proper motion observed (-0.0017±0.0033″/yr; which is insignificantly different from a constant). If the low mass star B_4 is gravitationally bound to the B group the B_1B_4 separation should be roughly constant over these three years. The observed rms scatter from a constant value is indeed a mere ±0.0019″, suggesting the whole θ^1 Ori B group is likely physically bound together. The first data point is an speckle observation from the 6-m SAO telescope (Schertl et al. 2003), the next point is from our Gemini/Hokupa'a observations and the last data point is from the MMT AO observations.

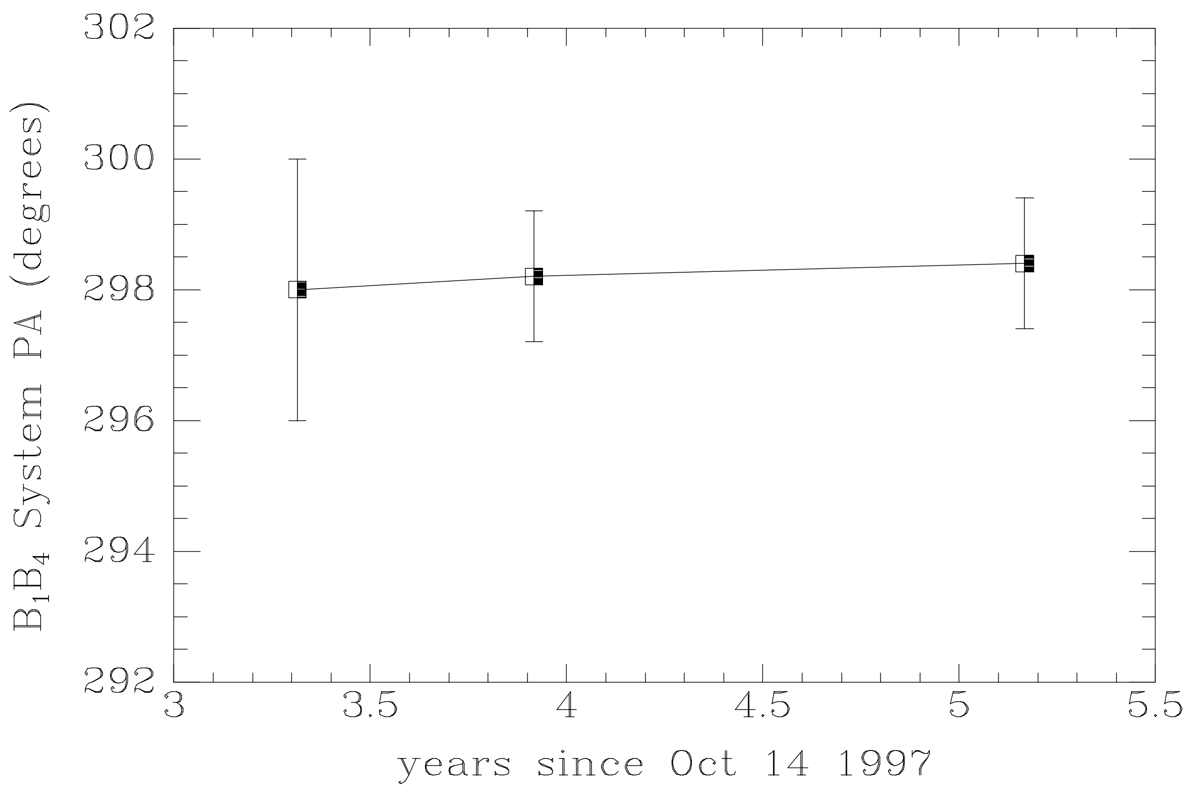

Fig. 14.— The position angle between θ^1 Ori B_1 and B_4. Note how over three years of observation there has been no significant relative proper motion observed (0.18±0.9°/yr which is insignificantly different from a constant). The error from a constant value is a mere ±0.3°.The first data point is a speckle observation from the 6-m SAO telescope (Schertl et al. 2003), the next point is from our Gemini/Hokupa'a observations and the last data point is from the MMT AO observations.