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MMT, ROSAT, Hipparcos

DISCOVERY OF A FAINT COMPANION TO ALCOR USING MMT/AO 5 μM IMAGING[1]

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ABSTRACT

We report the detection of a faint stellar companion to the famous nearby A5V star Alcor (80 UMa). The companion has M-band ($\lambda = 4.8\,\mu$m) magnitude 8.8 and projected separation 1".11 (28 AU) from Alcor. The companion is most likely a low-mass ($\sim$0.3 $M_{\odot}$) active star which is responsible for Alcor's X-ray emission detected by ROSAT ($L_X \simeq 10^{28.3}$ erg/s). Alcor is a nuclear member of the Ursa Major star cluster (UMa; d $\simeq$ 25 pc, age $\simeq$ 0.5 Gyr), and has been occasionally mentioned as a possible distant (709") companion of the stellar quadruple Mizar (ζ UMa). Comparing the revised Hipparcos proper motion for Alcor with the mean motion for other UMa nuclear members shows that Alcor has a peculiar velocity of 1.1 km/s, which is comparable to the predicted velocity amplitude induced by the newly-discovered companion ($\sim$1 km/s). Using a precise dynamical parallax for Mizar and the revised Hipparcos parallax for Alcor, we find that Mizar and Alcor are physically separated by 0.36 ± 0.19 pc (74 $\pm$ 39 kAU; minimum 18 kAU), and their velocity vectors are marginally consistent (χ^2 probability 6%). Given their close proximity and concordant motions we suggest that the Mizar quadruple and the Alcor binary be together considered the 2nd closest stellar sextuplet. The addition of Mizar-Alcor to the census of stellar multiples with six or more components effectively doubles the local density of such systems within the local volume (d < 40 pc).

Subject headings: binaries: close – binaries: general – binaries: visual – open clusters and associations: individual (Ursa Major) – stars: individual (Alcor, Mizar)

1. INTRODUCTION

Knowing the distribution of companion masses as a function of orbital separation and primary mass, is fundamental to understanding the nature of fragmentation of collapsing molecular cloud cores and star formation itself. Evidence suggests that the binary frequency is a function of stellar mass such that higher mass stars have a higher binary frequency (c.f. Lada 2006). Whether the distribution of companion masses is consistent with having been drawn from the field star "system" initial mass function across the mass spectrum of primaries remains to be demonstrated. In addition, high order multiples provides important dynamical constraints to star formation in clusters and associations (Goodwin et al. 2007; Parker et al. 2009).

The stars Mizar (ζ UMa) and Alcor (80 UMa) hold an esteemed place in astronomical lore as perhaps the most famous optical double. Situated in the middle of the handle of the Big Dipper, Mizar and Alcor are separated by 11'.8. At this separation, the pair is resolvable by the naked eye, and indeed the system is famous for its use in testing vision among many cultures (Allen 1899). Claims of the physicality of the Mizar-Alcor binary varies across the literature, ranging from confident statements that the two comprise an unphysical "optical double", to the pair being comprised of two unbound members of the same star cluster (Ursa Major), to being listed as a definite bound multiple system.

Mizar is resolved in modest telescopes into a 14".4 binary (Perryman & ESA 1997) with a probable period of thousands of years. Mizar A is a nearly equal-mass, double-lined spectroscopic binary with period 20.54 days and eccentricity of 0.53 (Pourbaix 2000). Mizar B is a spectroscopic binary with period 175.57 days and an eccentricity of 0.46 (Gutmann 1965). The discovery of Mizar as a binary is often mistakenly attributed to Giovanni Battista Riccioli around 1650 (e.g. Allen 1899; Burnham 1978), however Galileo's protege and collaborator Benedetto Castelli reported resolving Mizar in a letter to Galileo dated 7 January 1617. Galileo himself resolved the binary and later recorded his measurements on 15 January 1617 (Ondra 2004; Siebert 2005). Besides Alcor, an additional bright star lies within 8' of Mizar – the 7th magnitude star HD 116798 ("Stella Ludoviciana" or "Sidus Ludovicianum"; Allen 1899; Siebert 2005). This star can now be trivially ruled out as being physically associated with Mizar or Alcor based on its small proper motion and inconsistent spectrophotometric distance. The ensemble of Mizar, Alcor, and Sidus Ludovicianum provided the first testing ground for attempts to solve one of the cosmological conundrums of the 17th century: trying detecting stellar parallax to confirm the then controversial heliocentric model. Lodovico Ramponi, in a letter to Galileo in 1611, sketched out the concept that optical double stars of different magnitudes (presumed to be identical suns lying at a range of distances) would provide definite proof of heliocentrism

[1] Observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.
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through the detection of differential parallax. Galileo sketched an aperture mask to detect differential parallax in his observations of Mizar, Alcor, and Sidus Ludovicianum (Siebert 2005). Unfortunately for Galileo, definitive detection of stellar parallax would not be forthcoming for two more centuries (Bessel 1838).

The Mizar-Alcor system contained further surprises and astronomical firsts. Mizar A & B, and Alcor, were together the first resolved multiple star system photographed on 27 April 1857 (Bond 1857)[3]. While working on the Henry Draper Memorial project at Harvard College Observatory, Antonia Maury found Mizar A to be the first spectroscopic binary (reported by Pickering 1890). Later, Mizar B was reported to be a single-lined spectroscopic binary; independently by two contemporaneous studies a century ago (Ludendorff 1908; Frost 1908). Mizar A was also one of the first binary stars to be resolved using an optical interferometer (Pease 1925).

The Gliese CNS3 catalog lists the Mizar-Alcor system as a "wide binary and multiple system", and the 17th widest multiple system in their census of solar neighborhood stars (Gliese & Jahreiss 1988). Alcor is a bright (V_{mag} = 3.99) A5Vn star situated 708".55 from Mizar A (Gray & Garrison 1989; Fabricius et al. 2002). Alcor's properties are summarized in Table 1. Alcor was also detected as an X-ray source in both pointed observations and the All-Sky Survey of the ROSAT X-ray observatory (Voges et al. 1999; ROSAT Consortium 2000; White et al. 2000). X-ray emission is rare among A-type stars (Simon et al. 1995; Schröder & Schmitt 2007). X-ray emission among A-type stars is often proposed to be emitted from the coronae of low-mass companions, and indeed the majority of X-ray emitting A-type stars show some signs of multiplicity (Schröder & Schmitt 2007).

Alcor has been reported to have rapid radial velocity variations (Frost 1908; Heard 1949) – possibly intrinsic to the star itself. The star is often flagged as "SB" (Johnson & Morgan 1953; Hoffleit 1964; Gliese & Jahreiß 1991), but no orbit has ever been reported. Frost (1908) stated that there is "no doubt that Alcor is also a spectroscopic binary", and that the displacement and multiplicity of the Mg λ4481 and Balmer lines "succeed each other so rapidly that I have found it necessary to have spectrograms of this star made in continuous succession for several hours". Frost did not publish his radial velocities. Heard (1949) stated "there is a fair degree of probability that Alcor varies in velocity". Their observations over a ~9 year span appear to be of very low quality (two observations 4 minutes apart had radial velocities that differed by 33 km s^{-1}). Heard (1949) estimated a velocity amplitude of 6 km s^{-1} (no uncertainty), but no period was reported. The most recent comprehensive assessment of the binarity of Alcor was reported by Abt (1965). In his large survey of A-star multiplicity, Abt (1965) measured 13 additional radial velocities in 1959-1961, and said the radial velocities "show a slightly excessive scatter." Taking into account previously published velocities, Abt concluded that Alcor's velocity was "Constant:", and he considered the star to be single.

In this paper, we (1) report the discovery of a faint companion to Alcor at separation 1".1 with the 6.5-m MMT telescope using the adaptive secondary (MMT/AO), (2) argue that the nature of the companion is most likely a low-mass dwarf which is also responsible for Alcor's X-ray emission detected by ROSAT and subtle peculiar motion with respect to the mean motion for Ursa Major nucleus members, and (3) present evidence that the astrometry of the Mizar-Alcor system is consistent with the Mizar quadruple and Alcor double being physically associated, making the Mizar-Alcor a probable sextuplet, and the 2nd closest such multiple known.

[3] 150 years to the month before the images reported in this contribution.

TABLE 1
Properties of Alcor

Property	Value	Ref.
Parallax	39.91 ± 0.13 mas	1
Distance	25.06 ± 0.08 pc	1
μ_α	120.21 ± 0.12 mas yr^{-1}	1
μ_δ	-16.04 ± 0.14 mas yr^{-1}	1
RV	-9.6 ± 1.0 km s^{-1}	2
V_{mag}	3.99 mag	1
B-V	0.169 ± 0.006 mag	1
V-I_c	0.19 ± 0.03 mag	1
L'_{mag}	3.65 mag	3
T_{eff}	8030 K	4
Spec. Type	A5Vn	5
BC_V	-0.02 mag	6
M_V	2.00 ± 0.01 mag	7
log($L/L_\odot$)	1.11 ± 0.01 dex	8
L_X	$10^{28.34}$ erg s^{-1}	9
Mass	1.8 $M_\odot$	10
Age	0.5 ± 0.1 Gyr	11
U, V, W	+14.3, +2.7, -9.3 km s^{-1}	12
	($\pm$0.5, 0.7, 0.6 km s^{-1})	12

Note. — References: (1) van Leeuwen (2007), distance is inverse of parallax, (2) Gontcharov (2006), (3) Kidger & Martín-Luis (2003), (4) mean value from Blackwell & Lynas-Gray (1998), Cenarro et al. (2001), Gray et al. (2003), and Le Borgne et al. (2003), (5) Gray & Garrison (1989), (6) from adopted T_{eff} and tables of Flower (1996), (7) from adopted V magnitude and parallax, assuming zero extinction, (8) from adopted M_V and BC_V, (9) soft X-ray luminosity (0.2-2.4 keV) in ROSAT band, calculated using count-rate and hardness ratio HR1 from Voges et al. (2000), energy conversion factor from Fleming et al. (1995), and the adopted parallax, (10) combining T_{eff} and log($L/L_\odot$) values with z=0.02 evolutionary tracks of Lejeune & Schaerer (2001), (11) UMa cluster age from King et al. (2003), (12) Galactic Cartesian velocity vector, calculated in §3.4.1.

2. OBSERVATIONS

As part of a recently completed survey to image brown dwarf and exoplanet companions to nearby intermediate-mass stars (Mamajek et al., in prep.; Kenworthy et al. 2009), the star Alcor was imaged with the Clio 3-5 μm imager in conjunction with the adaptive secondary mirror on the 6.5-m MMT telescope (Brusa et al. 2004). Clio is a high well depth InSB detector with 320 × 256 pixels and 49 mas pixels and field of view of 15".6 × 12".4 at M-band when attached to the MMT (Sivanandam et al. 2006; Hinz et al. 2006; Heinze et al. 2008).

Alcor was imaged at M-band with Clio and MMT/AO on 08 Apr 2007 (start UT 08:26) for a total integration time of 2697 sec (0.75 hr). Observations were stopped due to cloud cover. Alcor was beam-switch nodded 5".5 along the long axis of Clio after each 5 images. The obser-

TABLE 2
Photometry and Astrometry for Alcor B

Property	Value
ΔM	5.175 ± 0.013 mag
m_M	8.82 ± 0.05 mag
M_M	6.83 ± 0.05 mag
PA (θ)	208°.82 ± 0°.08
sep (ρ)	1109.5 ± 2 mas (27.8 AU @ 25.1 pc)
epoch	JD 2454199.35 (J2007.267)

vations of Alcor consist of a series of 129 images of 20.91 second exposures; each consisting of 100 coadded frames of 209.1 msec. The short exposure time was selected to keep the sky background counts below the nonlinearity threshold for Clio (∼40k ADU). The primary star is unsaturated in all the frames, with a peak count value of approximately 3800 counts above the local background level, and a PSF with a full width half maximum of 4.0 pixels (0".20). The Clio images were taken with a Barr Associates M-band filter with half power range of 4.47-5.06 μm and central peak wavelength of 4.77 μm.

3. ANALYSIS

3.1. *Astrometry*

We use a custom pipeline to reduce Clio data, with steps including automatic amplifier noise pattern correction and beamswitching (described in Kenworthy et al. 2009). Bad pixels are interpolated over with a 3×3 pixel median filter. The science images are resampled with bilinear interpolation, and rotated with North at the top of the image and East to the left.

We use observations of the triple system HD 100831 (HIP 56622; STF 1553AB) to calibrate the plate scale and orientation of the detector. The system consists of a single primary star and a spectroscopic, unresolved (separation < 1 mas) binary system with a period of approximately 3000 years. The primary and secondary are separated by approximately 6.1 arcseconds. This system has been observed over several epochs ranging back to 1890, showing that the orbital motion is closely approximated by a linear trend in position angle and angular separation. We use astrometry from Hipparcos (Perryman & ESA 1997) and from Sinachopoulos et al. (2007) from 1990 through to 2005 to extrapolate the PA and separation at the observation epoch. We predict that the position angle of the HD 100831 binary at epoch 2007.267 was 165°.74 ± 0°.08 with separation 6".136 ± 0".010. Using these values we calculate the plate scale and orientation of the Clio detector on the April 2007 run, two days after carrying out the Alcor B observations. Our plate scale (48.56 ± 0.10 mas pix^{-1}) is similar to the plate scales determined during other Clio observation runs. The Position Angle offset for Clio differs from previous runs by 0.5 degrees, consistent with the repeatability of mounting Clio over several runs. The errors in the measurement of Alcor B astrometry is dominated by the astrometric uncertainty in the orbit of HD 100831.

Alcor B is clearly seen in all 129 science images. We determine the position offset and magnitude difference between A and B by using Alcor A as a reference PSF for each of the frames. Alcor B sits in the halo of uncorrected light from Alcor A, and so we estimate the local background about Alcor B by removing the azimuthal

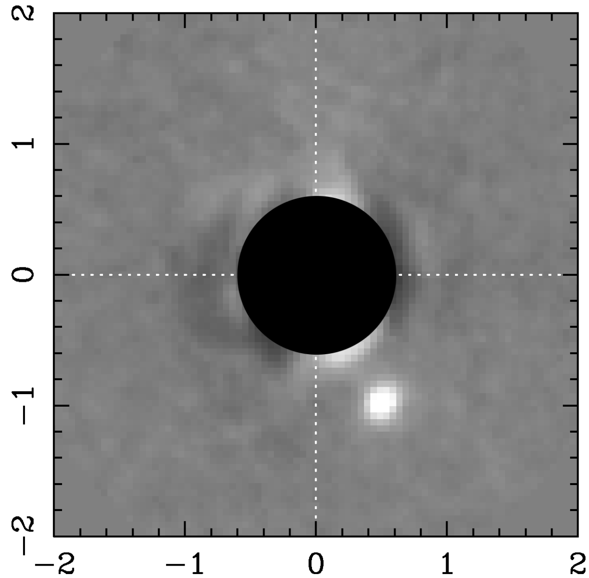

Fig. 1.— Image of Alcor B as imaged with Clio at the MMT. The ordinate and abscissa are RA and Dec offset from Alcor, respectively, in arcseconds. North is up and east is left, and the inner 0".6 radius of the subtracted PSF of Alcor A is masked. Ten exposures of 20.1 seconds are averaged together to form a total exposure of 201 seconds. Background subtraction is carried out by removing the azimuthal medians of annuli centered on Alcor A. The color scale is from -15 to +15 counts.

median of a set of nested concentric rings centered on Alcor A out to a radius of 3". The reference PSF is then scaled in intensity and translated over to the location of Alcor B, and subtracted off. We then use a custom fitting routine to explore this three parameter space (X and Y offsets, plus the magnitude difference) by minimizing the residuals of this subtraction in a circular aperture centered on the position of Alcor B, using Alcor A as a PSF reference. Since we are able to use the unsaturated image of Alcor A as our PSF reference, we do not have to approximate the PSF of Alcor B or make any other simplifying assumptions, so we use an iterative process to determine the best fit parameters. If the fitting routine does not converge to a solution within 40 iterations, the fit is discarded (79 images are retained). Including the astrometric uncertainties determined from the calibrator binary, the mean values are separation $\rho = 1".1095 \pm 0".0020$ and position angle $\theta = 208°.82 \pm 0°.08$.

3.2. *Photometry*

Using the same fitting routine, we measure a magnitude difference of $\Delta M = 5.175 \pm 0.013$ mag with respect to Alcor A. The absolute photometric uncertainty for Alcor B is dominated by the uncertainty in the M-band magnitude for Alcor A, which is unmeasured. Alcor A is an A5Vn star with negligible reddening. Combining its L' magnitude (3.65; Kidger & Martín-Luis 2003, we assume ±0.01 mag uncertainty) with the predicted intrinsic L'-M color for A5V stars (0.01; Bessell & Brett 1988), and assuming a conservative total uncertainty in the intrinsic color and photometric conversion of ±0.05 mag, we estimate the M magnitude of Alcor to be 3.64 ± 0.05 mag. This leads to an apparent M-band magnitude for Alcor B of m_M = 8.82 ± 0.05 mag.

3.3. *X-ray Emission*

Alcor has an X-ray counterpart in the ROSAT All Sky Survey (1RXS J132513.8+545920; Voges et al. 2000) situated 4" away from Alcor's optical position, but with X-ray positional uncertainty of 13". The total exposure time was 552 seconds, and the RASS observations were taken between 27 Nov 1990 and 1 Dec 1990. Using the soft X-ray counts in the ROSAT band (0.2-2.4 keV) and hardness ratio HR1 from Voges et al. (2000), and using the energy conversion factor from Fleming et al. (1995), and the adopted parallax from van Leeuwen (2007), we estimate an X-ray luminosity of $10^{28.28}$ erg s^{-1}. The hardness ratio HR1 is defined following Schmitt et al. (1995) and Voges et al. (1999) as HR1 = (B-A)/(B+A), where A is the ROSAT X-ray count-rate in the 0.1-0.4 keV band, and B is the count-rate in the 0.5-2.0 keV band. Alcor was also detected by ROSAT in a 2608 sec observation on 8 May 1992, and is reported in the Second ROSAT Source Catalog of Pointed Observations (ROSAT Consortium 2000) as X-ray source 2RXP J1325.9+545914. No position error is given, but the X-ray source is 3".5 away from Alcor, and given typical ROSAT positional uncertainties, it is extremely likely that the Alcor system is responsible for the X-ray emission. Using the soft X-ray counts in the ROSAT band (0.04679 ct s^{-1}; 0.2-2.4 keV) and the reported hardness ratio (HR1 = -0.37), and using the energy conversion factor from Fleming et al. (1995), and the adopted parallax from van Leeuwen (2007), we estimate an X-ray luminosity of $10^{28.35}$ erg s^{-1}.

We adopt an exposure time-weighted mean ROSAT X-ray luminosity of $10^{28.34}$ erg s^{-1}. Independently, and using the same archival ROSAT data, Schröder & Schmitt (2007) report Alcor as an unresolved ROSAT X-ray source with luminosity $L_X = 10^{28.27}$ erg s^{-1}. This is only 17% lower than the mean value we calculate, but within the systematic uncertainties for X-ray luminosity estimation using ROSAT count rates and hardness ratios.

3.4. *Kinematic Information*

3.4.1. *Velocity of Alcor*

Combining the position, proper motion, and parallax from the revised Hipparcos (van Leeuwen 2007) with the radial velocity from the compiled catalog of Gontcharov (2006), we estimate the velocity of Alcor in Galactic Cartesian coordinates to be U, V, W = +14.2, +3.0, -9.4 km s^{-1}(±0.4, 0.7, 0.6 km s^{-1}). The best modern long-baseline proper motion for Alcor comes from the Tycho-2 catalog (Høg et al. 2000), and combining the revised Hipparcos parallax and Gontcharov (2006) radial velocity with the Tycho-2 proper motion gives a velocity of U, V, W = +14.3, +2.7, -9.3 km s^{-1}(±0.5, 0.7, 0.6 km s^{-1}), i.e. negligibly different (<0.3 km s^{-1} per component) from that calculated using the short-baseline revised Hipparcos proper motion.

3.4.2. *Velocity of Mizar*

In order to calculate an accurate center-of-mass velocity for the Mizar quadruple, we need an estimate of the systemic radial velocity for the system. The mass of Mizar B and its companion is not well-constrained, so it is difficult to calculate an accurate systemic velocity for Mizar. The systemic velocity of Mizar A is -6.3 ± 0.4 km s^{-1} (Pourbaix 2000) and that for B is -9.3 ± 0.1 km s^{-1} (Gutmann 1965). Guttman (1965) estimates that the Mizar B binary is ∼80% of the mass of the Mizar A binary. Adopting the mass of the Mizar A binary (4.9 $M_\odot$) from Hummel et al. (1998), then the mass of Mizar B is likely to be ∼3.9 $M_\odot$. Using these masses, we can estimate a mass-weighted systemic radial velocity of the Mizar AB quadruple system of -7.6 km s^{-1}, with a conservative uncertainty of ∼1 km s^{-1}.

We combine the revised Hipparcos trigonometric parallax from (38.01 ± 1.71 mas van Leeuwen 2007) and the dynamical parallax from (39.4 ± 0.3 mas Hummel et al. 1998) to estimate a weighted mean parallax of ϖ = 39.36 ± 0.30 mas. Using this systemic radial velocity, the weighted mean parallax, and the proper motion from van Leeuwen (2007), we calculate a velocity of Mizar of U, V, W = 14.6, 3.1, -7.1 km s^{-1} (±0.5, 0.7, 0.6 km s^{-1}).

3.4.3. *Velocity of Ursa Major Star Cluster*

From the revised Hipparcos astrometry (van Leeuwen 2007), published mean radial velocities (Gontcharov 2006), and nucleus membership from King et al. (2003), we find the mean velocity vector of the UMa nucleus to be U, V, W = 15.0, 2.8, -8.1 (± 0.4, 0.7, 1.0) km s^{-1}, a convergent point of α, δ = 300°.9, -31°.0 with S_{tot} = 17.3 ± 0.6 km s^{-1}. Our UMa cluster velocity compares well to the unweighted mean measured by King et al. (2003): U, V, W = 14.2, 2.8, -8.7 (± 0.7, 1.3, 1.8) km s^{-1}. A figure showing the positions and proper motion vectors for the UMa nuclear members is shown in Figure 2.

Using the calculated velocity vectors for Alcor, Mizar, and the UMa cluster, we find that Alcor shares the motion of UMa to within 1.4 ± 1.6 km s^{-1}, and Mizar shares the motion of UMa to within 1.3 ± 1.7 km s^{-1}. Hence both Alcor and Mizar are consistent with being kinematic UMa members (although we discuss the intrinsic velocity dispersion of the group further in §3.4.4). Subtracting the motion of Alcor from that of Mizar yields ΔU, ΔV, ΔW = -0.4, 0.0, -2.4 km s^{-1} (±0.7, 1.0, 0.9 km s^{-1}), and a difference in motion of 2.7 ± 0.8 km s^{-1}. Testing the hypothesis that the motion of Alcor is consistent with that of Mizar, the difference results in χ^2/d.o.f. = 7.4/3 and a χ^2 probability of 6%. Hence, the motion of Alcor and Mizar are consistent at the ∼2σ level, given the observational uncertainties.

We find both Alcor and Mizar to be comoving within 1.5 km s^{-1} of the mean UMa cluster motion. *What is the probability that a field A-type star would have a velocity as similar as Alcor's and Mizar's is to the UMa nucleus?* To answer this question, we cross-referenced the revised Hipparcos astrometry catalog (van Leeuwen 2007) with the Gontcharov (2006) compiled radial velocity catalog, and calculate UVW velocities for A-type stars (spectral types from Perryman & ESA 1997) with parallaxes of >10 mas (d < 100 pc) and parallax uncertainties of <12.5%. Given these constraints, we compile a catalog of velocities for 1018 A-type stars, 6 of which are known UMa nucleus members. After removing the 6 UMa A-type nucleus members, we find that only 1 A-type star within 100 pc (HIP 75678) has a velocity within 2 km s^{-1} of the UMa nucleus (1/1012 ≃ 0.1%). The typical error in the space motions for the A-type field stars is ∼2.5 km s^{-1}(∼1.4 km s^{-1} per component). We find that only 2.5% (25/1012) of field A-type stars have mo-

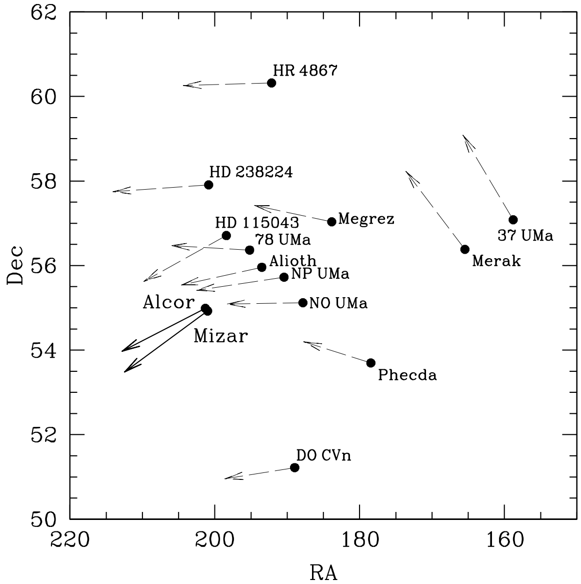

Fig. 2.— Map of the UMa nuclear members in equatorial coordinates. Arrows indicate 200 kyr of proper motion. Census of UMa nucleus members comes from King et al. (2003), except for HD 238224 (Mamajek, in prep.). The dispersion amongst the (mostly convergent) proper motion vectors comes from a mix of geometric projection effects (the stars are at high declination) and peculiar motions (dispersion in tangential motions at the ∼1 km s^{-1} level). Mizar, Alcor, and the central, most massive UMa nucleus member Alioth have distances of 25.4 ± 0.2 pc, 25.1 ± 0.1 pc, and 25.3 ± 0.1 pc, respectively. Using the revised Hipparcos parallaxes (van Leeuwen 2007), the mean distance to the 14 UMa nucleus systems is 25.2 ± 0.3 pc – implying that Mizar-Alcor is codistant with the other nuclear members.

tions within 5 km s^{-1} of the UMa velocity vector. Hence, given its velocity alone, a conservative upper limit to the probability that Alcor might be an interloper to the UMa cluster is probably in the range of ∼0.1-2.5 %.

3.4.4. *Peculiar Motion of Alcor*

Independent of the radial velocity values, we can test how consistent Alcor's tangential (proper) motion is with UMa membership. Following the techniques discussed in Mamajek (2005), we find that Alcor's revised Hipparcos proper motion toward the UMa convergent point is μ_υ = 120.9 ± 0.1 mas yr^{-1}, and the perpendicular motion is μ_τ = 9.2 ± 0.1 mas yr^{-1}. At Alcor's distance this translates into a peculiar motion of 1.1 ± 0.1 km s^{-1}.

What velocity dispersion do we expect among the UMa nuclear members if the cluster is in virial equilibrium? From the census of UMa nuclear members from King et al. (2003) and the astrometry from van Leeuwen (2007), we estimate that the stellar mass of the UMa nucleus is approximately ∼28 M$_\odot$ and encloses a volume of ∼100 pc^3. The predicted 1D virial velocity for this stellar system is 0.1 km s^{-1}, suggesting that the peculiar velocity of 1.1 ± 0.1 km s^{-1} is significantly deviant. However, the distribution of peculiar motions for the rest of the UMa nucleus members, using the revised Hipparcos proper motions and the mentioned convergent point, is consistent with a 1D velocity dispersion of 1.1 ± 0.2 km s^{-1}, implying that Alcor's peculiar motion is not unusual compared to the other nuclear members. Our estimate of the 1D velocity dispersion is within the errors of that estimated by Chupina et al. (2001) of 1.33 km s^{-1} (no uncertainty). The UMa nucleus has 9 stars with peculiar velocities of <0.5 km s^{-1}, while the other outliers have peculiar velocities between 0.9 and 4.4 km s^{-1}. *All* of these UMa nucleus stars with peculiar motions of >0.5 km s^{-1} have been claimed to be stellar multiples (including HD 109011, 111456, 113139, 238224, Mizar, and now Alcor). So the likely reason that the observed 1D velocity dispersion of the UMa nucleus is ∼10× the predicted virial velocity is probably due to the effects of stellar multiplicity on the proper motions, rather than this long-lived ∼0.5 Gyr-old nucleus being unbound.

Given Alcor's position in the UMa nucleus, similarity of motion with other UMa nucleus members, proximity to UMa member Mizar, HR diagram position consistent with other UMa members, and the inherent low space density of A dwarfs (local density is ∼10^{-3} pc^{-3})[4], it is extremely unlikely that Alcor could be an interloper. We conclude that Alcor is an UMa member, and that its motion is plausibly perturbed at the 1 km s^{-1} level by the newly discovered companion star.

4. DISCUSSION

4.1. *The Nature of Alcor B*

We investigate three scenarios for the nature of Alcor B: (1) interloper, (2) white dwarf bound companion, (3) low-mass main sequence bound companion. If the companion is bound, its age should be identical to that of Alcor A (i.e. 0.5 ± 0.1 Gyr; King et al. 2003), and its apparent magnitude translates into an absolute M-band magnitude of M_M = 6.83 ± 0.05 (adopting Alcor's parallax of $\varpi = 39.91 \pm 0.13$ mas).

• Scenario 1 (interloper): The companion is very bright for a background object. Alcor is at high Galactic latitude (b = +61°.5). The number of M-band (approximately the same as IRAC 4.5 μm) background stars can be estimated from Fig. 1 of Fazio et al. (2004). An approximate fit to the differential number counts in the Bootes field (b = +67.3) due to stars is log$_{10}$(dN/dM) [num mag^{-1} deg^{-2}] ≃ -2.0 + 0.33 mag$_{4.5\,\mu m}$. The predicted density of background stars brighter than mag$_M$ < 8.8 is ∼12 deg^{-2}, and the number predicted within 1".11 of Alcor is ∼3×10^{-6}. In our initial imaging survey of ∼20 such A-type stars, we would have expected to find ∼6×10^{-5} interlopers of brighter magnitude and closer proximity. We also empirically measure the density of K$_s$-band ($\lambda = 2.2\,\mu$m) stars brighter than K$_s$ mag of 8.8 near Alcor in the 2MASS catalog (Cutri et al. 2003), and find 10 deg^{-2}. Since most stars have K$_s$-M colors of ∼0.0, the 2MASS K$_s$ density provides a useful check on the differential number counts provided by Fazio et al. (2004). If the star is a background star, it does not provide an explanation for Alcor's X-ray emission or peculiar motion with respect to the UMa nucleus. We ascribe a negligible probability (∼10$^{-4.2}$) that Alcor's faint companion is a background star.

• Scenario 2 (white dwarf): Given the age of the UMa cluster, any members whose initial mass was originally ∼2.9-7 M$_\odot$ are now white dwarfs, most likely in the mass range ∼0.7-1.1 M$_\odot$ (Lejeune & Schaerer 2001; Kalirai 2009). If we hypothesize that Alcor B was originally a 0.5 Gyr-old 2.9 M$_\odot$ star, it should now be a cooling 0.7

[4] Calculated using the census of stars within 10 pc from the Henry et al. RECONS project: http://www.chara.gsu.edu/RECONS/.

$M_\odot$ white dwarf star (Kalirai 2009). The white dwarf cooling tracks of Bergeron et al. (1995)[5] do not include M-band, but does include K-band. If we assume K-M color of zero, then $M \simeq K \simeq 8.8$ implies a white dwarf cooling age of ∼270 kyr and a predicted $T_{\rm eff} \simeq 100{,}000$ K. While we can not completely rule out the companion being a white dwarf with the data in hand, we can estimate a rough probability for B being a white dwarf: P $\sim N_{stars}\, \Delta\tau_{WD}/\tau_{age} \sim 0.01$, where N_{stars} is the number of stars in the UMa nucleus (∼20), $\Delta\tau_{WD}$ is the time interval of rapid evolution that we are concerned with (the white dwarf cooling timescale), and τ_{age} is the age of the cluster (0.5 ± 0.1 Gyr; King et al. 2003). While a white dwarf companion might explain Alcor's peculiar motion, it does not explain the X-ray emission, and it appears very unlikely (P $\sim 10^{-2}$) that we would serendipitously discover a very luminous, hot, white dwarf companion during this very short period of its evolution.

• Scenario 3 (low-mass dwarf companion): Using the log(age/yr) = 8.7 evolutionary tracks of Baraffe et al. (1998), a low-mass star with absolute M magnitude of 6.83 translates into a mass of 0.30 $M_\odot$ (and predicted $T_{\rm eff} = 3437$ K, $\log(L/L_\odot)$ = -1.99, $L_{\rm bol} = 10^{31.60}$ erg s^{-1}, spectral type ∼M2V). If the low-mass dwarf is responsible for the ROSAT X-ray emission ($L_X = 10^{28.34}$ erg s^{-1}), then $\log(L_X/L_{bol})$ = -3.26. Such an X-ray luminosity is typical of M dwarfs members of the similarly aged (625 Myr) Hyades cluster (Stern et al. 1995). *The ROSAT X-ray emission of Alcor may be parsimoniously explained by the existence of a low-mass active companion.* If the observed orbital separation corresponds to the semimajor axis (27.8 AU), then A (with mass 1.8 $M_\odot$) and B (with mass 0.3 $M_\odot$) would have velocity amplitudes of 1.2 km s^{-1} and 7.0 km s^{-1}, respectively, and a predicted period of ∼100 yr. Remarkably, the predicted velocity amplitude for Alcor A is similar in magnitude to the measured peculiar motion of Alcor A with respect to the Ursa Major nucleus mean motion. It is doubtful that the observed companion could be responsible for the unconfirmed radial velocity variations observed over a 9-yr period by Heard (1949).

The hypotheses that the new companion is a background star or a white dwarf companion appears to be very low, with approximate probabilities of $\sim 10^{-4}$ and $\sim 10^{-2}$, respectively. Not only is the idea of the companion being physical very likely, but it provides a likely explanation for why Alcor is an X-ray source at the observed X-ray luminosity, and why Alcor's velocity is peculiar with respect to the Ursa Major mean motion at the ∼1 km s^{-1} level. We conclude that the companion is likely to be physical, and a low-mass (∼0.3 $M_\odot$) dwarf.

4.2. *Mizar-Alcor: A Hierarchical Sextuplet*

While Mizar and Alcor was considered a wide-separation binary by Gliese & Jahreiss (1988), the two stars were claimed to belong to different kinematic subunits within the UMa cluster by Chupina et al. (2001). As the question of whether Mizar and Alcor comprise a physical binary appears to be unanswered, we decided to explore the issue using modern astrometric data. We do this by exploring the extent to which Mizar and Alcor are comoving and codistant, and testing whether they could be a bound system.

How likely is it that two UMa nucleus members (e.g. Mizar and Alcor) would lie within 709" of each other but not constitute a multiple system? The UMa nucleus contains 15 systems within a ∼200 deg^2 region of sky (density of ∼0.8 stars deg^{-2}). Hence the number of predicted UMa members within 709" of a random UMa member is ∼0.1. So Mizar and Alcor are projected unusually close to one another if they do not constitute a physical subsystem, but are both UMa members.

To what degree are Mizar and Alcor consistent with being co-distant? For calculating distances to Alcor and Mizar, we adopt the parallax for Alcor listed in Table 1 (39.91 ± 0.13 mas; van Leeuwen 2007) and the parallax for Mizar calculated in Sec. 3.4.2 (39.36 ± 0.30 mas). The parallaxes are consistent with distances of 25.4 ± 0.2 pc for Mizar and 25.1 ± 0.1 pc for Alcor, respectively, and only differ by 2.7σ. Monte Carlo modeling of the parallax uncertainties leads to a physical separation between the Mizar and Alcor systems of $\Delta = 0.36 \pm 0.19$ pc (74 ± 39 kAU). The minimum possible separation is Δ_{min} = 17.8 kAU. For reference, the most massive and central UMa member − Alioth − lies at d = 25.3 ± 0.1 pc (from revised Hipparcos parallax; van Leeuwen 2007), and so is statistically consistent with being codistant with Mizar-Alcor. Using the adopted distances, Alcor is physically 2.01 ± 0.02 pc away from the central UMa star Alioth.

We already demonstrated in §3.4.3 that Alcor and Mizar differ in motion by only 2.7±0.8 km s^{-1}, and are marginally statistically consistent with co-motion. *What orbital velocities would we expect for the Alcor binary and Mizar quadruple?* If we assume a total mass for the Mizar system of ∼9 $M_\odot$, a total mass of ∼2 $M_\odot$ for the Alcor binary, and a presumed orbital semimajor axis of 74 kAU, then one would predict relative orbital velocities of ∼0.3 km s^{-1} for the Alcor center-of-mass and ∼0.07 km s^{-1} for the center-of-mass of the Mizar quadruple. If Alcor and Mizar are actually at their minimum possible separation (17.8 kAU), then the velocity amplitudes would be ∼0.6 km s^{-1} (Mizar) and ∼0.1 km s^{-1} (Alcor). Hence the center-of-mass motions of Alcor and Mizar are likely to be within <0.7 km s^{-1} along any axis, and within the uncertainties of the current astrometric measurements.

5. SUMMARY

We conclude that a low-mass main sequence companion physically bound to Alcor A is the most likely explanation for the nature of Alcor B. Future observations confirming common proper motion, and multiband imaging or spectroscopy confirming that the companion is indeed a M-type dwarf, are necessary to confirm this hypothesis. The newly discovered companion is unlikely to be responsible for the short timespan radial velocity variations observed by Frost (1908) and Heard (1949). The case for the Alcor binary and the Mizar quadruple constituting a bound sextuplet with physical separation $\Delta = 0.36 \pm 0.19$ pc (74 ± 39 kAU) is also strong, given the statistical consistency of their space velocities.

Recent simulations of multiple star evolution in dense stellar clusters by Parker et al. (2009) shows that clusters with initial densities of $>10^2\ M_\odot\ {\rm pc}^{-3}$ preclude the production of binaries with separations of $>10^4$ AU like Mizar-Alcor. Indeed, Parker et al. (2009) conclude that "[b]inaries with separations $> 10^4$ AU are 'always soft' -

[5] http://www.astro.umontreal.ca/∼bergeron/CoolingModels/

any cluster will destroy such binaries (if they could even form in the first place)" and that such binaries must form in isolation. Mizar-Alcor would appear to be a counter-example. Given the range of initial stellar densities probed by the Parker et al. study, one can conclude that a reasonable upper limit on the initial density of the UMa cluster is $<10^2$ $M_\odot$ pc^{-3}.

In comparing the Mizar-Alcor sextuplet to the known multiple star population (Tokovinin 1997; Eggleton & Tokovinin 2008), it appears that that Mizar-Alcor (d $\simeq$ 25 pc) is the 2nd known closest multiple system with 6 (or more) components after Castor (d $\simeq$ 16 pc). The addition of Mizar-Alcor to the census of known multiple systems with 6 or more components brings the census of such systems within 100 pc to 6, and effectively doubles the density of such systems within a the 40 pc local volume.

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REFERENCES

Abt, H. A. 1965, ApJS, 11, 429
Aitken, R. G. 1918, New York [D. C. McMurtrie] 1918.,
Allen, R. H. 1899, New York, Leipzig [etc.] G.E. Stechert
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
Bergeron, P., Saumon, D., & Wesemael, F. 1995, ApJ, 443, 764
Bessel, F. W. 1838, MNRAS, 4, 152
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Blackwell, D. E., & Lynas-Gray, A. E. 1998, A&AS, 129, 505
Bond, G. 1857, MNRAS, 17, 230
Brusa, G., Miller, D. L., Kenworthy, M. A., Fisher, D. L., & Riccardi, A. 2004, Proc. SPIE, 5490, 23
Burnham, R., Jr. 1978, Burnham's celestial handbook, Vols. 1, 2, and 3, by Burnham, R., Jr.. New York (NY, USA): Dover Publ., Inc, 138 p.,
Cenarro, A. J., Cardiel, N., Gorgas, J., Peletier, R. F., Vazdekis, A., & Prada, F. 2001, MNRAS, 326, 959
Chupina, N. V., Reva, V. G., & Vereshchagin, S. V. 2001, A&A, 371, 115
Cutri, R. M., et al. 2003, The IRSA 2MASS All-Sky Point Source Catalog, NASA/IPAC Infrared Science Archive. http://irsa.ipac.caltech.edu/applications/Gator/,
Eggleton, P. P., & Tokovinin, A. A. 2008, MNRAS, 389, 869
Fabricius, C., Høg, E., Makarov, V. V., Mason, B. D., Wycoff, G. L., & Urban, S. E. 2002, A&A, 384, 180
Fazio, G. G., et al. 2004, ApJS, 154, 39
Fleming, T. A., Schmitt, J. H. M. M., & Giampapa, M. S. 1995, ApJ, 450, 401
Flower, P. J. 1996, ApJ, 469, 355
Frost, E. B. 1908, Astronomische Nachrichten, 177, 171
Gliese, W., & Jahreiß, H. 1991, On: The Astronomical Data Center CD-ROM: Selected Astronomical Catalogs, Vol. I; L.E. Brotzmann, S.E. Gesser (eds.), NASA/Astronomical Data Center, Goddard Space Flight Center, Greenbelt, MD
Gliese, W., & Jahreiss, H. 1988, Ap&SS, 142, 49
Gontcharov, G. A. 2006, Astronomy Letters, 32, 759
Goodwin, S. P., Kroupa, P., Goodman, A., & Burkert, A. 2007, Protostars and Planets V, 133
Gray, R. O., & Garrison, R. F. 1989, ApJS, 70, 623
Gray, R. O., Corbally, C. J., Garrison, R. F., McFadden, M. T., & Robinson, P. E. 2003, AJ, 126, 2048
Gutmann, F. 1965, Publications of the Dominion Astrophysical Observatory Victoria, 12, 361
Heard, J. F. 1949, ApJ, 109, 185
Heinze, A. N., Hinz, P. M., Kenworthy, M., Miller, D., & Sivanandam, S. 2008, ApJ, 688, 583
Hinz, P. M., Heinze, A. N., Sivanandam, S., Miller, D. L., Kenworthy, M. A., Brusa, G., Freed, M., & Angel, J. R. P. 2006, ApJ, 653, 1486
Høg, E., et al. 2000, A&A, 355, L27
Hoffleit, D. 1964, New Haven, Conn.: Yale University Observatory, 1964, 3rd Ed.
Hummel, C. A., Mozurkewich, D., Armstrong, J. T., Hajian, A. R., Elias, N. M., II, & Hutter, D. J. 1998, AJ, 116, 2536
Johnson, H. L., & Morgan, W. W. 1953, ApJ, 117, 313
Kalirai, J. S. 2009, IAU Symposium, 258, 299
Kalirai, J. S., Ventura, P., Richer, H. B., Fahlman, G. G., Durrell, P. R., D'Antona, F., & Marconi, G. 2001, AJ, 122, 3239
Kenworthy, M. A., Mamajek, E. E., Hinz, P. M., Meyer, M. R., Heinze, A. N., Miller, D. L., Sivanandam, S., & Freed, M. 2009, ApJ, 697, 1928
Kidger, M. R., & Martín-Luis, F. 2003, AJ, 125, 3311
King, J. R., Villarreal, A. R., Soderblom, D. R., Gulliver, A. F., & Adelman, S. J. 2003, AJ, 125, 1980
Lada, C. J. 2006, ApJ, 640, L63
Le Borgne, J.-F., et al. 2003, A&A, 402, 433
Lejeune, T., & Schaerer, D. 2001, A&A, 366, 538
Ludendorff, H. 1908, Astronomische Nachrichten, 177, 7
Lynn, W. T. 1906, The Observatory, 29, 391
Mamajek, E. E. 2005, ApJ, 634, 1385
Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2001, AJ, 122, 3466
Ondra, L. 2004, S&T, 108, 72
Parker, R. J., Goodwin, S. P., Kroupa, P., & Kouwenhoven, M. B. N. 2009, MNRAS, 397, 1577
Pease, F. G. 1925, PASP, 37, 155
Perryman, M. A. C., & ESA 1997, ESA Special Publication, 1200,
Pickering, E. C. 1890, The Observatory, 13, 80
Pourbaix, D. 2000, A&AS, 145, 215
ROSAT Consortium, 2000, ROSAT News 72 (25 May 2000), Vizier catalog IX/30
Schmitt, J. H. M. M., Fleming, T. A., & Giampapa, M. S. 1995, ApJ, 450, 392
Schröder, C., & Schmitt, J. H. M. M. 2007, A&A, 475, 677
Siebert, H. 2005, Journal for the History of Astronomy, 36, 251
Simon, T., Drake, S. A., & Kim, P. D. 1995, PASP, 107, 1034
Sinachopoulos, D., Gavras, P., Dionatos, O., Ducourant, C., & Medupe, T. 2007, A&A, 472, 1055
Sivanandam, S., Hinz, P. M., Heinze, A. N., Freed, M., & Breuninger, A. H. 2006, Proc. SPIE, 6269,
Stern, R. A., Schmitt, J. H. M. M., & Kahabka, P. T. 1995, ApJ, 448, 683
Tokovinin, A. A. 1997, A&AS, 124, 75
van Leeuwen, F. 2007, Astrophysics and Space Science Library, 350,
Voges, W., et al. 1999, A&A, 349, 389
Voges, W., et al. 2000, IAU Circ., 7432, 1
White, N. E., Giommi, P., & Angelini, L., 2000, The WGACAT version of the ROSAT PSPC Catalogue, Rev. 1, Laboratory for High Energy Astrophysics (LHEA/NASA), Greenbelt