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DETECTION OF A VERY LOW MASS COMPANION TO THE ASTROMETRIC BINARY GLIESE 105A

D. A. Golimowski
Center for Astrophysical Sciences, Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218
AND
T. Nakajima, S. R. Kulkarni, and B. R. Oppenheimer
Palomar Observatory, 105-24, California Institute of Technology, Pasadena, CA 91125
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ABSTRACT

Optical coronagraph images of the high proper motion astrometric binary Gl 105A reveal a very red companion, Gl 105C, located 3."27 from Gl 105A at P.A. 287°. At this location, it is not clear whether Gl 105C can fully account for the astrometric perturbation of Gl 105A. Aperture photometry gives $I_C = 12.6$ and $R_C - I_C = 3.7$ for Gl 105C, indicating that it is a very low mass M dwarf. Using the observed I_C, an empirical M_I versus $I-K$ relation, and an assumed distance of 8.2 pc to Gl 105A, $M_K = 9.7$ is derived for Gl 105C. An empirical mass-M_K relation for low-mass stars suggests a mass of 0.084 $M_\odot$ for Gl 105C, which is just above the minimum mass for stable hydrogen burning. Gl 105C was not detected in previous K-band searches; its detection demonstrates the usefulness of optical coronagraphy for identifying very low mass objects.

Subject headings: binaries: close — stars: low-mass, brown dwarfs — stars: individual (Gliese 105A)

1. INTRODUCTION

The astrometric binary Gl 105A (HR 753, HD 16160, BD +6°398; $V = 5.81$; spectral type K3 V) is the primary component of a triple system. The secondary component, Gl 105B ($V = 11.7$; dM4), is located 165" to the southeast and exhibits common proper motion with the primary star (van Maanen 1938). Gl 105A has been included in two long-term astrometric studies conducted at Sproul Observatory (Lippincott 1973; Heintz & Cantor 1994, hereafter HC94) and McCormick Observatory (Martin & Ianna 1975; Ianna 1992, hereafter I92). These studies suggest that the mass of the unseen companion is 0.08–0.13 $M_\odot$ and that the apparent separation of the astrometric components must at times be greater than 2". Attempts to resolve the astrometric companion visually (Lippincott 1973; HC94) and by optical or infrared speckle interferometry (McAlister 1978; Hartkopf & McAlister 1984; McCarthy 1995) have been unsuccessful.

We have twice observed Gl 105A as part of an ongoing coronagraphic search for brown dwarf companions to stars within 20 pc of the Sun (Nakajima et al. 1994, hereafter Paper I). We have initially concentrated on those stars at high Galactic latitudes ($|b| > 40°$) having large proper motions (greater than 0."4 yr^{-1}). These constraints facilitate the detection of companions by reducing background source confusion and by permitting short-term tests of common proper motion. With a proper motion of 2."32 yr^{-1}, $b = -48°$, and $\pi = 0."115$ (I92) or 0."129 (HC94), Gl 105A fully satisfies our search criteria.

In this *Letter* we present the first direct evidence of a very low mass (VLM) companion to Gl 105A, obtained through coronagraphic imaging in the R and I bandpasses. We compare the observed position of the companion with those positions expected from the orbital elements computed by I92 and HC94. Finally, we obtain an estimate of the companion's mass which is just above the minimum mass for stable hydrogen burning.

2. OBSERVATIONS AND DATA REDUCTION

Observations of Gl 105A were conducted in 1993 October and 1994 October using the Johns Hopkins University's Adaptive Optics Coronagraph (AOC) at the Palomar Observatory 60 inch (1.5 m) telescope. The observing dates and conditions are listed in columns (1)–(3) of Table 1. The AOC employs an image-stabilization system for improved resolution and pupil-plane apodization for the suppression of light diffracted by the telescope aperture (Golimowski et al. 1992). The AOC reimaged the telescope focal plane at f/52 onto a Tektronix 1024 × 1024 24 μm pixel CCD, providing a field of view of ~1' × 1'. The CCD pixels were binned 2 × 2 during readout. A circular occulting mask of radius 2."15 was inserted at the reimaged focal plane preceding the CCD. Once acquired, Gl 105A was centered behind the occulting mask and stabilized by applying image-motion corrections with a tip-tilt mirror every 10 ms.

To determine the positions and proper motions of stars in the imaged fields, accurate knowledge of the CCD's plate scale and orientation is required. The relative changes in the plate scale and orientation between 1993 October and 1994 October were determined by cross-correlating the positions of three background stars in the field around Gl 830 imaged in each period. The plate scales differed by 0.25%; the position angles differed by 2°2. Absolute calibration of the plate scale and orientation for either period was attempted by imaging a fixed wide binary with reportedly well-known separation and position angle. However, the positions listed in the PPM Star Catalogue (Röser & Bastian 1991) and the Hipparchos Input Catalogue (Turon et al. 1992, hereafter HIC) for these binaries (ADS 5705AC in 1993, and ADS 1683AB in 1994) led to inconsistent results for the Gl 830 field. Consequently, the correct plate scale and orientation for 1993 October were obtained by cross-correlating the positions of five background stars in the field around 68 Oph imaged in both 1993 June and 1993

TABLE 1

SYNOPSIS OF OBSERVATIONS

	Sky Conditions		CCD Information			Exposure Log			
Date (1)	Seeing[a] (arcsec) (2)	Transparency[b] (Δ mag) (3)	Type (4)	Plate Scale (arcsec pixel^{-1}) (5)	P.A. (deg) (6)	Filter (7)	Air Mass (8)	Time (s) (9)	Number of Exposures (10)
1993 Oct 25......	1.20	±0.2	TEK 1024^2 (thick)	0.1165 ± 0.0003	2.3 ± 0.2	R_C	1.12	200	3
						I_C	1.12	200	3
1994 Oct 27......	1.05	±0.1	TEK 1024^2 (thin)	0.1162 ± 0.0003	0.1 ± 0.2	r	1.12	120	5
						I_C	1.12	150	4

[a] FWHM of motion-corrected image.
[b] Sky transparency based on fluctuations of standard-star measurements.

October with the same CCD. Absolute calibration of the 1993 June images had been successfully achieved by imaging the fixed binary ADS 14279AB and by confirming the proper motion of Gl 581 observed between 1993 June and 1994 April. The plate scale and CCD position angle for 1993 June were determined to be 0".1169 pixel^{-1} and 0°.9, respectively. (This plate scale is a revision of that previously reported in Paper I.) The results for 1993 October and 1994 October are presented in columns (4)–(6) of Table 1.

In 1993, exposures of Gl 105A were recorded using standard Kron-Cousins R_C and I_C bandpass filters (Bessell 1990). For very red stars, $R_C - I_C$ saturates around 2.5, primarily because of severe absorption by photospheric TiO (Leggett & Hawkins 1988). This saturation may also be due in part to the extended red tail of R_C which overlaps I_C redward of 7000 Å. This extended tail causes the effective wavelength of R_C to move significantly redward for increasingly redder stars (Bessell 1986). The migration of $\lambda_{\rm eff}$, however, is substantially reduced in the Thuan-Gunn photometric system (Thuan & Gunn 1976; Tinney, Reid, & Mould 1993). Thus, in the 1994 follow-up observation of Gl 105A, Thuan-Gunn r was used to enhance the image contrast of the very red companion candidate. I_C was used in place of Thuan-Gunn i, since the two are effectively identical (Tinney et al. 1993). A log of all exposures of Gl 105A is given in columns (7)–(10) of Table 1. Throughout each night's observations, images of several photometric standard stars were recorded to monitor variable seeing conditions and sky transparency.

The raw CCD images were reduced to flux-calibrated images using the NOAO IRAF software to perform the conventional techniques of bias subtraction, division by a flat field, and interpolation over bad pixels and cosmic-ray events. The multiple exposures for each filter were then summed. Visual inspection of the calibrated data showed three stellar sources within the field, one of which lay within the seeing disk of Gl 105A. To identify other potential companions lying near the occulted star, subtraction of the seeing disk was required. A bivariate polynomial which best fitted the seeing disk was obtained and then subtracted from the image. (The presence of faint stellar sources would not significantly affect the polynomial fit.) No more companion candidates were identified above the I-magnitude detection limits of 17 and 18.5 at 2".5 and 4", respectively, from Gl 105A (Paper I). To obtain photometric measurements of the near-field source, a more accurate subtraction of the seeing disk was performed by obtaining polynomial fits to the radial seeing profiles oriented at least 30° to either side of the source. Subtraction of the seeing disk within 7" of Gl 105A was complete to ~3%. The photometric uncertainties ascribed to the residuals of the subtraction are given in § 3. Brightness measurements of all field sources were obtained using conventional aperture photometry.

3. RESULTS

Figure 1 shows the central 14".5 × 14".5 section of the 1993 I_C image of Gl 105A. As is evident from the image, the occulting mask is translucent and permits unsaturated exposure of the core of the occulted star's seeing disk. Consequently, the position of Gl 105A may be determined without the need for comparably bright field stars or a precise telescope offset. Although the mask appears uniformly translucent within the core of the seeing disk (the centroid varies by $\lesssim 0.2$ pixel as the radius of computation is increased), we assume a conservative uncertainty of ±1 pixel for the centroid of Gl 105A. In Figure 1, a 70° section of the seeing disk has been removed to reveal a faint stellar source located 3".30 ± 0".12 from Gl 105A at P.A. 287° ± 2°. Similar analysis of the 1994 I_C image showed the same source located 3".24 ± 0".14 from Gl 105A at P.A. = 287° ± 2°. Given the large proper motion of Gl 105A, the companionship of the source is undeniable. Therefore, we hereafter refer to the companion as Gl 105C.

The magnitudes and positions of Gl 105C and the two other field stars (designated FS 1 and FS 2) are listed in Table 2. The uncertainties of these magnitudes reflect the combined effects of the seeing-disk subtraction, photon noise, and fluctuations in sky transparency. The residuals of the seeing-disk subtraction contributed an uncertainty of ~0.2 mag to the R_C and r magnitudes of Gl 105C, but they contributed negligibly to the photometric error in I_C. Combining these measurements yields $R_C - I_C = 3.7 \pm 0.4$ and $r - i \approx r - I_C = 3.7 \pm 0.3$ for Gl 105C. These colors are over a magnitude greater than the reddest $R-I$ colors reported from recent optical surveys of late M dwarfs (Bessell 1991; Leggett 1992; Tinney et al. 1993; Jarrett, Dickman, & Herbst 1994).

Figure 2 depicts the observed location of Gl 105C and the positions of the astrometric companion at epoch 1994.82 expected from the best-fit photocentric orbits of I92 and HC94. We detected no change in the relative position of Gl 105C between the 1993 and 1994 observations beyond that attributable to the uncertainty of our measurements. If Gl 105C is the heretofore unresolved astrometric companion, its observed position is quite different from those computed from the apparent orbits of I92 and HC 94. The apparent orbits themselves, however, are quite discordant, so the candidacy of Gl 105C as sole astrometric companion cannot be rejected. I92 and HC94

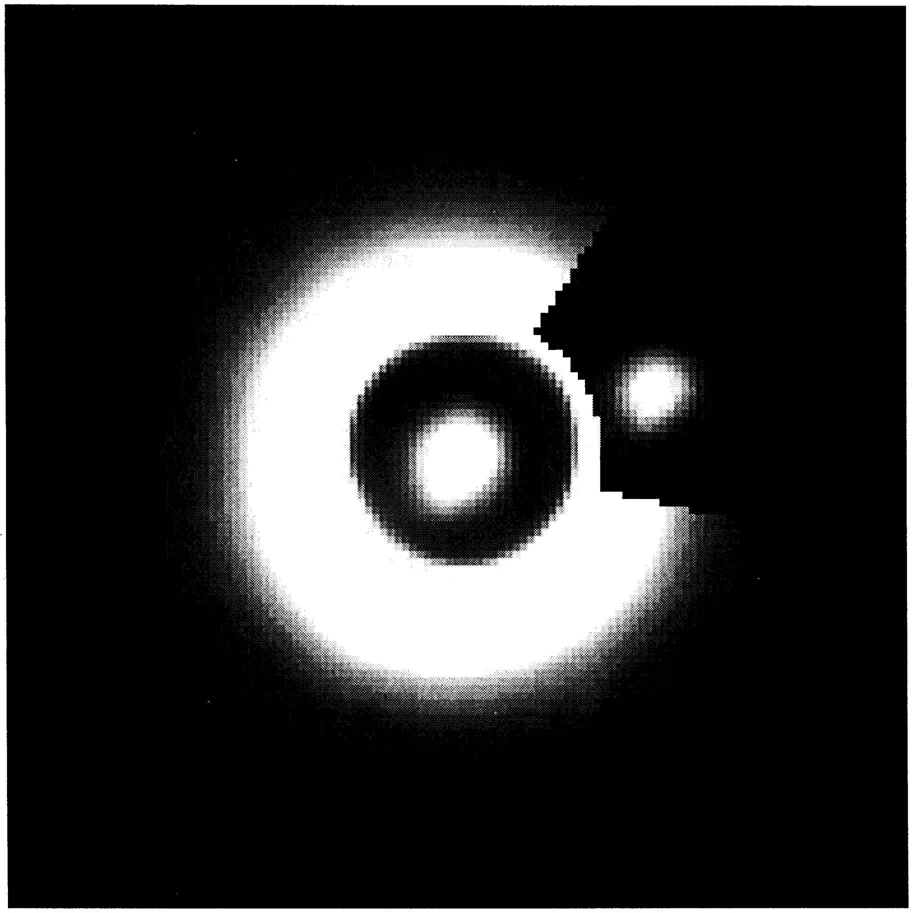

FIG. 1.—1993 I_C image of Gl 105A obtained with the Adaptive Optics Coronagraph. The field is 14″.5 × 14″.5, with north at the top and east to the left. The 2″.15 radius occulting mask is slightly transparent and reveals the core of the occulted star's seeing disk. Part of the seeing disk has been subtracted to reveal the companion, Gl 105C, located 3″.30 from Gl 105A at P.A. 287°. The companion has an I_C magnitude of 12.6.

do agree that the period of the astrometric binary is ~60 yr and the companion should be near periastron, so positional uncertainties are likely to be largest around the current epoch.

Before continuing the discussion of Gl 105C, a few remarks concerning the other two field stars, FS 1 and FS 2, should be made. The observed $R_C - I_C$ colors for FS 1 and FS 2 are 0.6 ± 0.3 and 1.0 ± 0.4, respectively. These colors suggest spectral types of F8–M0 for FS 1 and K4–M4 for FS 2. Using the faint ends of these spectral ranges and the apparent magnitudes listed in Table 2, we compute a minimum distance of 500 pc to these stars. Treating FS 1 and FS 2 as fixed background stars, we compute for Gl 105A a proper motion of 2″.23 ± 0″.22 yr^{-1} at P.A. 49° ± 5°, which is consistent with that given in HIC. Thus, FS 1 and FS 2 provide verification of the CCD plate scale and orientation (§ 2).

4. DISCUSSION

The detection of Gl 105C in R and I clearly demonstrates the usefulness of optical coronagraphy for identifying VLM stars or brown dwarf candidates. However, $R - I$ is not a good indicator of spectral types later than M6 because of indistinct bandpass limits and emission blanketing by increasing numbers of molecular species (Bessell 1991). The extreme value of $R_C - I_C = 3.7$ measured for Gl 105C, rather than giving an

TABLE 2

MAGNITUDES AND POSITIONS OF STARS IN THE FIELD OF GL 105A

Epoch (1)	Star (2)	R_C (3)	r (4)	I_C (5)	Position Relative to Gl 105A: $\Delta\alpha$ (6)	Position Relative to Gl 105A: $\Delta\delta$ (7)
1993.82......	Gl 105C	16.5 ± 0.3	...	12.8 ± 0.2	−3″.16 ± 0″.08	+0″.96 ± 0″.09
	FS 1	15.9 ± 0.2	...	15.3 ± 0.2	−19.74 ± 0.11	+14.83 ± 0.11
	FS 2	17.7 ± 0.3	...	16.7 ± 0.3	−16.31 ± 0.10	+15.58 ± 0.15
1994.82......	Gl 105C	...	16.2 ± 0.2	12.5 ± 0.1	−3.11 ± 0.08	+0.93 ± 0.11
	FS 1	...	15.7 ± 0.1	15.0 ± 0.1	−21.41 ± 0.11	+13.35 ± 0.12
	FS 2	...	17.3 ± 0.1	16.4 ± 0.1	−17.98 ± 0.11	+14.11 ± 0.11

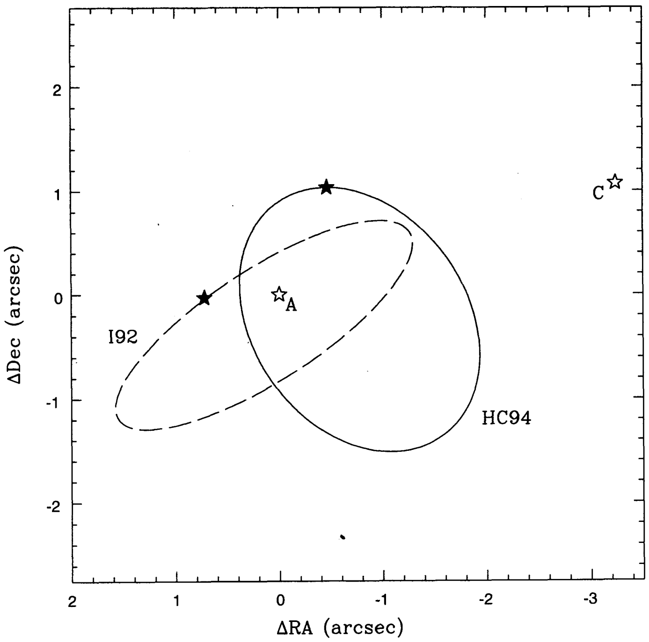

FIG. 2.—Comparison of the observed location of Gl 105C (*open star labeled "C"*) and the expected orbital positions of the astrometric companion (*filled stars*) at epoch 1994.82. Positions are relative to Gl 105A (*open star labeled "A"*). The apparent orbits are computed from the best-fit photocentric orbits of Ianna (1992; *dashed curve*) and Heintz & Cantor (1994, *solid curve*).

accurate indication of the star's effective temperature, more likely reflects a photospheric idiosyncrasy of the star. Nevertheless, Gl 105C must certainly be among the coolest, least massive stars so far identified.

Using the average of the parallaxes measured for Gl 105A by I92 and HC94, we obtain a distance of 8.19 ± 0.67 pc to the Gl 105 system. We therefore compute for Gl 105C an absolute magnitude of $M_I = 13.1 \pm 0.2$. From the M_I versus $I-K$ relation of Leggett (1992), we infer $M_K = 9.7 \pm 0.2$ for Gl 105C, which satisfies the $M_K > 9$ limit set by McCarthy (1995) using infrared speckle imaging. (At our request, G. Neugebauer and K. Matthews imaged Gl 105A on 1993 November 25 using Palomar Observatory's f/70 Cassegrain infrared camera at the 200 inch (5 m) Hale Telescope. Gl 105C was detected in a 0.5 s exposure at K, but poor observing conditions limited photometry to a crude estimate of $K = 8$–10.) Henry & McCarthy (1993) have derived an empirical mass-luminosity relation for low-mass stars with $3.07 \leq M_K \leq 9.81$. We obtain for Gl 105C a mass of $0.084 \pm 0.008\ M_\odot$, which is just above the theoretical minimum mass for stable hydrogen burning (D'Antona & Mazzitelli 1985). This mass is consistent with the astrometric estimate of $0.08\ M_\odot$ reported by HC94, but much lower than the $0.13\ M_\odot$ estimate of I92. The consistency with HC94 notwithstanding, the most unambiguous means of determining the mass of Gl 105C is through long-term monitoring of the binary orbit.

Although the astrometric accuracy of our coronagraphic technique is sufficient for establishing the companionship of Gl 105C within 1 year, it is insufficient for measuring the orbital motion of Gl 105C within that time. Our 1993 and 1994 images of the Gl 105 system effectively constitute single-epoch observations. Therefore, we are presently unable to refine the photocentric orbits of I92 and HC94 or to provide independent dynamic-mass measurements of Gl 105C. It is fortunate, however, that our detection of Gl 105C has occurred within 5 years of periastron passage (I92; HC94). If Gl 105C is the astrometric companion, observational determination of the relative orbit and component masses may be attained within 10 years.

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Note added in proof.—Since the completion of this Letter, D. W. McCarthy, Jr., has communicated that the infrared speckle search diameter was 3″.9, so Gl 105C could not have been detected using this technique.