A SEARCH FOR WIDE COMPANIONS TO THE EXTRASOLAR PLANETARY SYSTEM HR 8799

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ABSTRACT

The extrasolar planetary system around HR 8799 is the first multiplanet system ever imaged. It is also, by a wide margin, the highest mass system with >27 Jupiters of planetary mass past 25 AU. This is a remarkable system with no analog in any other known planetary system. In the first part of this paper, we investigated the nature of two faint objects imaged near the system. These objects are considerably fainter ($H = 20.4$ and $21.6$ mag) and more distant (projected separations of 612 and 534 AU) than the three known planetary companions b, c, and d (68–24 AU). It is possible that these two objects could be lower mass planets (of mass $\sim 5M_{\text{Jup}}$ and $\sim 3M_{\text{Jup}}$) that have been scattered to wider orbits. We make the first direct comparison of newly reduced archival Gemini adaptive optics images to archival Hubble Space Telescope/NICMOS images. With nearly a decade between these epochs, we can accurately assess the proper motion nature of each candidate companion. We find that both objects are unbound to HR 8799 and are background. We estimate that HR 8799 has no companions of $H < 22$ from $\sim 5''$ to $15''$. Any scattered giant planets in the HR 8799 system are $> 600$ AU or less than $3M_{\text{Jup}}$ in mass. In the second part of this paper, we search for any sign of a “reverse parallax signature” in the astrometric residuals of HR 8799. No such signal was found and we conclude, as expected, that HR 8799b has the same parallax as HR 8799A. In the third part of this paper, we carry out a search for wider common proper motion objects. We found one object within 1 deg$^2$ in the Palomar Observatory Sky Survey–Digitized Sky Survey images with similar ($< 2\sigma$) proper motions to HR 8799 at a separation of 4.0. We conclude that it is not likely a bound companion to HR 8799 based on available photometry.

Key words: planetary systems – stars: individual (HR 8799)

Online-only material: color figures

1. INTRODUCTION

There have been several surveys to directly image extrasolar planets from the ground with adaptive optics (AO) and from space with the Hubble Space Telescope (HST). Until very recently all surveys returned null results, and so it was generally assumed that wide, massive, extrasolar planets would be rare (at least around Sun-like stars) past 20 AU (Lafreniere et al. 2007a; Nielsen et al. 2008; Nielsen & Close 2009 and references within). However, in 2008 November, Marois et al. (2008) announced the discovery of three planets orbiting the A5V star HR 8799, based on near-IR imaging at the Keck and Gemini telescopes. Using data from Keck in 2004–2008 and Gemini in 2007–2008, they were able to establish common proper motions (assuming the non-common motion component $\sim 25$ mas yr$^{-1}$ for b and c was due to orbital motion of the planets around the star). The three planets, HR 8799b, c, and d orbit at approximately 68, 38, and 24 AU, respectively. Marois et al. (2008) estimate effective temperatures of 870, 1090, and 1090 K for the three planets, and arrive at estimates for mass of $7M_{\text{Jup}}$, $10M_{\text{Jup}}$, and $10M_{\text{Jup}}$. These estimates are based on the estimated 30–160 Myr age of HR 8799 and new atmospheric models for giant planets (see Marois et al. 2008 for more details).

It is possible that additional companions could be discovered during a search at wider separations. Theoretical studies (Scharf & Menou 2009; Veras et al. 2009 and references within) have predicted a population of giant planets at large separations (100–10,000 AU) from stars hosting relatively close-in planets, where the distant objects are dynamically scattered/pumped to large separations after system assembly. Scattering might be required to explain the unlikely, and possibly unstable, distribution of the three planets observed today (Fabrycky & Murray-Clay 2008; Gozdiewski & Migaszewski 2009). Such effects may explain the very wide, low-mass, companions GQ Lup B at $> 100$ AU (Neuhauser et al. 2005) and/or AB Pic B at $> 250$ AU (Chauvin et al. 2005). Detection of an even wider new member of the HR 8799 system would help to further understand the nature of this important system.

There is every reason to search the outer area around HR 8799 for new companions past 100 AU. Recently, it has been shown that there is a 70 $\mu$m spatially resolved excess around HR 8799, suggesting the debris disk extends from $\sim 90$ to 300 AU, with a tenuous halo from $\sim 300$ to 1000 AU (Su et al. 2009). In addition, there is certainly also the possible existence of very wide, low-mass, stellar companions that have not yet been detected. In this spirit, we will attempt to see if HR 8799 has any sign of common proper motion companions around it. It is clear, given the unique nature of the HR 8799 system, that a search for any wide ($> 100$ AU) companions is important and motivated this paper.

2. OBSERVATIONS AND REDUCTIONS

On 1998 October 30 UT, HST/NICMOS observed HR 8799 with its coronagraph, and two candidate companions were identified (Lowrance et al. 2005) in the roll-subtracted images. These faint point sources where reported at 13$''$ and 15$''$7 (540 AU and 619 AU) with $H$ magnitudes of 21.6 and 20.4, respectively. These are much wider separations than the three confirmed planets which were not discovered in the NICMOS data at the time, though one was later extracted from the older data set by Lafreniere et al. (2009). Figure 1 shows our own roll subtraction of the otherwise already pipeline reduced NICMOS data with the two objects identified. We also considered HR 8799’s high galactic latitude ($b = -35^\circ$), where previous surveys have found a lower density of background point sources within $\sim 16''$ (see Figure 2). Though certainly not
Figure 1. Roll-subtracted NICMOS F160W image from 1998, showing the two candidate companions “C” (to the left) and “B” (to the right) first identified by Lowrance et al. (2005)—each is circled in white. Each was visible in only one roll. The red circle around the star shows the 1"7 radius of HR 8799b. The NE compass is correct for the positive image (HR 8799B), however for HR 8799C (negative image) the compass should be rotated by 30° counterclockwise. (A color version of this figure is available in the online journal.)

Our WiFi ADI pipeline is very similar to standard ADI reduction and runs in a standard IRAF environment. In ADI, the telescope rotator is disabled and so the median of the images gives an estimate of the master point-spread function (PSF) without “contamination” from real objects on the sky. Then in normal ADI one must subtract the master PSF from each individual frame after a cross-correlation alignment of each frame as in Close et al. (2002). However, in WiFi ADI, the master PSF is created from non-aligned frames, then this PSF is subtracted off the individual images, in this manner all the bad pixels are optimally subtracted (since there are no image shifts—hence no incorrect interpolations of the bad pixels in the pipeline). Then these residual (PSF and bad-pixel-subtracted) images are sub-pixel aligned based on previously determined cross-correlation offsets. These aligned frames are then rotated by the parallactic angle and median combined (the subroutine to calculate the rotation angle is a custom script developed for Gemini data in Close et al. 2003). In summary, the key way that the WiFi ADI pipeline differs from the standard ADI is that it is optimized to preserve any faint off-axis objects that might fall past the edge of the IR array in the majority of the individual ADI frames. WiFi ADI accurately masks the effect of the great many bad pixels in the corners and edges of the NIRI array and uses a final median combine of all 118 re-rotated (master PSF-subtracted) images with no pixel clipping or rejection (so even the corner pixels of the individual frames are utilized in the final WiFi image). We also carefully offset each image by the mode of the outer region of each image, this allows the final median combine to be most sensitive in the outer regions of the image (with, of course, some loss of contrast inside 5′ compared to classic ADI).

Our WiFi ADI pipeline when used with the NIRI detector with its 0′0219 pixel−1 scale is then capable of creating a round WiFi ADI FOV of 31′71 in diameter when there is at least 90′ of field rotation during the ADI observation, and the object is stable (within 1–2 pixels) on the detector for all images. In the case of the 2007 October 25 Gemini HR 8799 data of Marois et al. (2008), the above assumptions are all true and our pipeline produced a final image (see Figure 3) of all H < 22 objects within ~5′–15′ of HR 8799. A detailed analysis of this image failed to detect any new companions of H < 22 (at 5σ), with a physical FWHM in a zone from ~5′ to 15′ of HR 8799. In summary, while both the NICMOS companions “C” and “B” were successfully detected, no new companions were detected by this WiFi ADI re-analysis of the Gemini 2007 data set.
3. ANALYSIS

3.1. Are “HR 8799B” and “HR 8799C” Background?

As is clear from Figures 1 and 3, there are two faint objects ~14″ from HR 8799. Based on detailed search of the literature and the VLT/Gemini/Subaru/HST archives, we have concluded that there has not been any published attempt to recover “B” or “C” until now. HR 8799A has a total proper motion of 119 mas yr⁻¹, so the recovery of the two candidate companions at the same separations as in 1988 with respect to HR 8799A would be an unambiguous confirmation of their physical association. These objects are both fainter than the HR 8799b–d planets (they would have masses of ~3 M_Jup and ~5 M_Jup on the 0.1 Gyr (Baraffe et al. 2002) COND tracks, which predict reasonable luminosities at these ages for higher mass objects; Close et al. 2007b). Such lower mass outer planets are consistent with being scattered by the heavier, close-in, planets.

In Figures 4 and 5, the 2007 positions of these two faint companions are shown. In both cases, the current positions are much closer to the locations calculated for distant background objects rather than physical companions. Indeed, they both can be rejected at the > 5σ level as physical (where, taking into account the distortions in the NIRI camera and systematic errors of 0.5% in platescale and 0.1” in P.A., we therefore adopt the total astrometric error of ~0.1″ = 1σ level). We note that if these were true physical companions at projected separations of 612 and 534 AU, then one would expect < 0.04 of orbital motion over nine years (completely inconsistent with the ~0.5 of motion observed). Therefore, our astrometry proves that the NICMOS companions of Lowrance et al. (2005) appear to be faint background objects unrelated to HR 8799A (see Table 1 for a detailed list of our astrometric measurements).

3.2. Does HR 8799b Show any Parallax Motion of a Background Object?

In the direction of Pegasus, most nearby stars appear to be moving toward the east–southeast. This is due to the Sun’s
motion in the opposite direction with respect to the Local Standard of Rest (LSR). In fact, the Sun’s space motion causes a stationary object (with respect to the LSR) at 39.9 pc to have a measured proper motion of 95.51 mas yr$^{-1}$ in R.A. and $-38.51$ mas yr$^{-1}$ decl. at the position of HR 8799A ($d = 39.9$ pc) has been removed. Hence, this is a plot of the true motions of HR 8799A, and extrasolar planet candidates HR 8799b and HR 8799c (all with respect to the LSR). It is interesting to note that HR 8799A, b, and c appear to have clearly different proper motions once the solar motion is subtracted. These differences in motion are most likely due to orbital motion of b and c around A (Marois et al. 2008).

For the planet HR 8799b (which has the largest timeline of observations), there appears to be some “scatter” in its measured position from A the nearly straight line expected for b’s long period orbit. The exact solution for a stable orbit of the massive planets b, c, and d is still somewhat uncertain (Fabrycky & Murray-Clay 2008).

In Figure 7, we consider the question what would this “scatter” resemble if b was actually a background object at 100 pc that had similar proper motions, by chance, to HR 8799A (at a distance of 100 pc, HR 8799b would roughly have the normal luminosity and colors of a background L dwarf). In this model, b’s position should show a “reverse” parallax with respect to HR 8799A with an amplitude of 60% that of HR 8799A’s parallax. We calculate the parallax of HR8799 in the usual manner (Biller & Close 2007) and then multiply by $-0.6$ to calculate “reverse” parallax.

In Figure 7, we show two models for the nature of HR 8799b motion: a background object at 100 pc and a simple “linear” planetary arc. The small triangles in Figure 7 denote time stamps in the 100 pc model to each observation date over the 9.885 yr period since the detection of b in a LOCI analysis of the NICMOS data set by Lafreniere et al. (2009). We note how neither the slightly curving “linear” orbit nor the 100 pc background model fit all data points simultaneously inside the 1σ error bars. The “linear” orbit is a simpler model with a better fit, but it certainly is not perfect since the reduced of $\chi^2 / \nu = 2$ gives an ~8% chance that it is the correct model—assuming no unknown systematic errors in the astrometry. On the other hand, a background source at 100 pc model can be rejected with 99.95% confidence ($\chi^2 / \nu \sim 4.4$). While there is still significant scatter in the linear orbit fit for b, we cannot reject it (we also do not, at this time, know what orbit to fit it to; Fabrycky & Murray-Clay 2008). However, we can reject the hypothesis that this scatter in HR 8799b’s position is reverse parallax due to it being a background object (assuming, of course, the reported astrometric values and errors are correct).

### 3.3. A Search for Other Common Proper Motion Companions to HR 8799

Even though the “B” and “C” objects are clearly background, there exists the possibility of other wider companions to HR 8799A that might be found by searching nearby for similar proper motion.

Our search started with the Naval Observatory Merged Astrometric Data Set (NOMAD) catalog (Zacharias et al. 2004). NOMAD combines several proper motion catalogs, including Hipparcos and Tycho. Most of its faint star entries are based on the USNO-B1 catalog (Monet et al. 2003). USNO-B1 is reported to be complete to $V \sim 21$; however, for objects

### Table 1

| Comp. Name | Epoch (UT) | $H$ (mag) | $\Delta$R.A. (arcsec) | $\Delta$Decl. (arcsec) | Sep. (arcsec) | P.A. (deg) | Ref. |
|------------|------------|-----------|----------------------|-----------------------|--------------|-----------|------|
| "B"       | 1998 Oct 30 | 21.6      | 3.756 ± 0.09         | 13.19 ± 0.09          | 13.71 ± 0.08 | 15.9 ± 0.1 | low05b |
| "B"       | 2007 Oct 25 | NA        | 3.24 ± 0.02          | 13.78 ± 0.07          | 14.15 ± 0.09 | 13.24 ± 0.07 | newc  |
| "C"       | 1998 Oct 30 | 20.4      | 14.29 ± 0.09         | $-6.45$ ± 0.09        | 15.68 ± 0.08 | 114.3 ± 0.1 | low05b |
| "C"       | 2007 Oct 25 | NA        | 13.42 ± 0.07         | $-6.40$ ± 0.03        | 14.86 ± 0.09 | 115.5 ± 0.1 | newc  |

Notes.

a The HR 8799A to B (or C) separation is as given by Lowrance et al. (2005), the errors are as given by Lowrance et al. (2005).

b Data from Lowrance et al. (2005).

c Data from our WiFi ADI reduction, astrometric errors dominated by 0.5% platescale errors across the field.
with \( \mu > 0.180 \) mas yr\(^{-1} \) as many as 99% of the objects are believed to be spurious (Gould 2003). These objects also have high uncertainties, causing contamination of our selection with spurious detections. We searched for any object within 0.5 of HR 8799 with a proper motion measurement within 2\( \sigma \) of HR 8799’s motion. At 39.9 pc, 0.5 corresponds to just over 7 \( \times 10^4 \) AU. This is a compromise between the number of false positives which must be ruled out and searching plausible separations for bound stellar companions.

Our query parameters produced 23 objects. All were faint, with high uncertainties. Levine (2005) provides a recipe for identifying real proper motion measurements in USNO-B1, which includes choosing objects with astrometric uncertainties < 999 mas and detections on at least four (of five) plates. Of the 23 objects, only six passed the astrometric uncertainty criterion, only five passed the number of detections criterion, and only one of these passed both. Taken together, these considerations made us doubtful that any of these objects would prove interesting as candidate stellar companions of HR 8799.

Despite the low likelihood of finding a candidate stellar companion, we manually checked the Palomar Observatory Sky Survey (POSS) POSS1 and POSS2 red images, obtained from the Digitized Sky Survey (DSS), to rule out each of the 23 objects as possible comoving companions of HR 8799. We used the proper motions to calculate the position at the mean epoch (USNO-B1 provides epoch 2000), and searched within a radius of \( \approx 20'' \) for any likely objects on the POSS images. As is common with such objects (Levine 2005), five of them proved to be associated with diffraction spikes of bright stars. For each of the remaining objects, we also queried the Sloan Digital Sky Survey (SDSS), which provides proper motion measurements cross-correlated with the USNO-B1. This process narrowed our list down to five objects for which we had detections on both POSS red images and could not be ruled out based on SDSS matches. For these objects, we performed our own measurements of proper motion using the technique described next. Based on our proper motion estimates, none of these are potential HR 8799 companions.

It has been reported that the USNO-B1 completeness may be as low as 65% for objects with \( \mu \approx 100 \) mas yr\(^{-1} \) (Levine 2005), which we assume propagates to NOMAD as well. This is the range of proper motion we are searching for, so we performed our own manual search of POSS1 (1951 August 12:08:12:00 UT) and POSS2 (1991 October 2 05:47:00 UT) Red DSS images to search for objects within 1 deg\(^2\) of HR 8799 with similar proper motions. The POSS1 image has a platescale of 1''/7 per pixel, whereas POSS2 has 1''/per pixel. We first magnified the POSS1 image to match the POSS2 platescale. Next, 25 background stars were selected, and their positions measured by centroiding in each image. We then compared their positions on the two images to determine the optimum rotation (\( \approx 0.7^\circ \)) to apply to the POSS1 image. We then selected an additional 25 background stars for a total of 50 stars spread across the images to build a background reference frame. Proper motions were then measured for individual stars by determining the average relative change in offset from the 50 background stars between the two images.

A different sample of 30 background stars was selected to test our technique. These were each compared to the 50 reference stars in each frame, and their proper motions were calculated from the average change in offset from the reference stars. The overall average of these measurements was \( \mu_{\alpha, \delta} = 0.81 \pm 3.50 \) mas yr\(^{-1} \) and \( \mu_{\alpha, \delta} = 4.92 \pm 3.04 \) mas yr\(^{-1} \). We subtract these offsets from the proper motion measurements made for individual stars.

For bright stars, there is a \( \pm 0.3 \) pixel uncertainty in centroid position (estimated from FWHM/\( \sqrt{\text{S/N}} \), where S/N is the signal-to-noise ratio). For the faintest objects that we considered, we found a \( \pm 0.95 \) pixel uncertainty (we estimate that our search is complete to a V magnitude of 21). Given the 40.139 year baseline between the two positions this amounts to \( \pm 10.6 \) mas yr\(^{-1} \) of proper motion uncertainty for bright stars, and \( \pm 33.5 \) mas yr\(^{-1} \) for faint objects. We combine these in quadrature with the standard error of our reference stars estimated from the 30 test stars above to obtain an estimated uncertainty of \( \approx \pm 11 \) mas yr\(^{-1} \) and \( \approx \pm 34 \) mas yr\(^{-1} \), respectively. The bright star case compares favorably with other POSS-based proper motion surveys, e.g., Lepine & Shara (2005) with \( \approx \pm 8 \) mas yr\(^{-1} \).

The 1° \( \times 1° \) area of sky centered on HR 8799 was searched manually by blinking between the registered POSS1 and POSS2 images. In order to compensate for subtle changes in magnification and field distortion, the image was re-centered on convenient background stars in each small area being searched. When a proper motion candidate was identified, its position was measured by centroiding and then its average change in offset relative to the 50 reference background stars was calculated.

As a check on our measurements, we compared our measurements of proper motion for two bright high proper motion stars in the field, NLTT 55870 and NLTT 55853, with POSS-based proper motion measurements (Lepine & Shara 2005). We measured \( (\mu_{\alpha, \delta}, \mu_{\alpha, \delta}) = (184.7, -43.5) \) and (178.2, -61.4), respectively, compared to the values of (185, -44) and (164, -63) reported by Lepine & Shara (2005). These measurements are consistent with each other within our bright star uncertainty of \( \approx \pm 11 \) mas yr\(^{-1} \).
We note that we are comparing measurements of proper motion relative to a sample of background stars, which is not the true absolute proper motion. Lepine & Shara (2005) discuss this systematic effect and attribute it to bulk motion of the reference stars. Taking NLTT 55870 and NLTT 55853 as an example, they apply correction offsets of \( \Delta \mu_{RA} = +4 \) mas yr\(^{-1}\) and \( \Delta \mu_{Decl} = -7 \) mas yr\(^{-1}\) to determine the absolute motion. We have not determined offsets for our own sample of reference stars, but given the agreement of our relative measurements with Lepine & Shara (2005) we apply the same offsets. The only definitive way to overcome this systematic effect for our purposes would be to simultaneously measure the proper motion of HR 8799 itself (which has accurate Hipparcos motions); however, it is badly saturated in the POSS images relative to nearby background stars, and is close to NLTT 55870 (discussed above), so we are confident that our detection of motion (non-zero at \( 3 \sigma \)) is not due to a local data reduction artifact. Because the SDSS uses USNO-B1 to calculate a prior epoch (Munn et al. 2004), which is itself based on POSS data and appears to be unreliable for this particular object, we do not combine our proper motion measurement with the SDSS measurement.

Its \( \mu_{Decl} \) is 1.3\( \sigma \) from the expected value of a common proper motion companion of HR 8799A; however, due to its proximity to HR 8799 it warrants further attention. At 39.9 pc, 4.0 corresponds to a separation of just under 10,000 AU, which is very wide but comparable to the widest bound systems (Close et al. 1990, 2007a). We discuss this object in more detail in Section 4.1.

4. DISCUSSION

The large mass of the three planets combined implies a very large initial stellar nebula, and their large orbital radii present challenges for both the core accretion (see Dodson-Robinson et al. 2009, and reference within) and even the gravitational instability theories of planet formation (Kratter et al. 2009). This system could perhaps be our best evidence for a new “non-core-accretion” mode of planet formation—hence the detection of any additional companions (planetary or higher in mass) is very important (Veras et al. 2009).

The observations of Marois et al. raise several interesting questions. The photometry shows a conspicuous lack of absorption by methane reddward of 1.6 \( \mu \)m, which is expected for such relatively cool (\( T_{eff} \sim 870 \) K) objects like HR 8799b—by all the “hot-start” (Baraffe et al. 2002; Burrows et al. 2003) or “core-accretion” (Fortney et al. 2008) synthetic spectra atmospheric models. Having performed photometry at several bands, Marois et al. attempted to fit spectral energy distributions (SEDs) generated by a hybrid atmospheric modeling code. The best-fit SEDs produced effective temperatures over 1400 K (Marois et al. 2008 online supplement). The authors argue that (with current atmospheric models) such high temperatures cannot be supported by the observed low luminosities unless the objects are unreasonably small or each has significant dust extinction and reddening. They claim three edge-on dust disks—which would be misaligned with the plane of their orbits (which is nearly face-on)—could explain such reddening, but the complexity of this hypothesis led Marois et al. to reject it.

We find that HR 8799 appears to be reddened by no more than \( A_H < 0.3 \) mag from Two Micron All Sky Survey (2MASS) colors in Marois et al. (2008), making it impossible that line-of-sight extinction to HR 8799A alone is the cause. However, the lack of a “reverse” parallax in the astrometric residuals of b’s separation from A (see Figure 7) offers strong proof that HR 8799b is a physical companion of A. Hence, it is unclear why HR 8799b appears underluminous for its best-fit model temperatures. Perhaps strongly non-LTE effects suppress methane in the outer atmosphere (Marois et al. 2008)? In any case, the discovery of another wide, reddened (or underluminous), companion would be very interesting in this system. Therefore, we need to investigate the properties of our remaining proper motion candidate.

4.1. Individual Object with Similar Proper Motion to HR 8799

Our catalog search and manual search of the POSS images for objects within 2\( \sigma \) of HR8799’s proper motion and within 0.5 of HR 8799 identified one candidate object. We will briefly discuss this “common proper motion” candidate (SDSS J230716.69+210509.1) noted in Table 2. We converted the SDSS photometry using the relations given by Jordi et al. (2006), obtaining \( V = 20.83 \pm 0.12 \) mag and \( B - V = 1.78 \pm 0.10 \) mag.
(the SDSS photometry is listed in Table 2). This is similar in color to an $\sim$M7 dwarf.

Our source is not in the 2MASS point source catalog, however there are $\approx 4\sigma$ detections just above the non-Gaussian noise in the $J$ and $K_s$ 2MASS images. We performed relative photometry using four nearby objects in the 2MASS catalog, arriving at estimates of $J = 16.8 \pm 0.6$ and $K_s = 15.49 \pm 0.7$. Its $V-K_s = 5.3 \pm 0.7$ is consistent with a mid M dwarf.

However, it is important to remember that our measurement of this object’s proper motion is only similar to HR 8799 at the 1.3$\sigma$ level. Moreover, it appears to be too faint and blue to have a physical association; its $B-V$ color and $V-K_s$ colors are consistent with a mid M dwarf, which would indicate a distance of $\sim 160$ pc (distance modulus of $\sim 6$ mag). We by no means claim that this is definitive as photometric parallaxes are very uncertain for mid to late M stars.

Finally, we note that the SDSS pipeline classifies this object as extended based on profile fits in the different filters. In the USNO-B1, it is listed as star-like (Star/Galaxy classifier $> 8$). Our detection of proper motion is inconsistent with a galaxy. As mentioned above our proper motion measurement is not consistent with the combined USNO-B1/SDSS proper motion measurement, though that result is likewise inconsistent with a galaxy. This object does appear to be in motion relative to the POSS1 epoch.

With these considerations, we conclude that this object is not likely a comoving companion but we cannot definitively rule this out. Due to its relative proximity to HR 8799 and the high interest in this system, further effort to first confirm our proper motion measurement, and then obtain more reliable IR photometry, and perhaps a spectrum is warranted.

There is still a need for future work in the search for wide companions to HR 8799. Due to the brightness of HR 8799 on survey images, there exists an annulus from $\approx 15^\prime < r < \approx 60^\prime$ which has not been adequately explored in this paper for stellar companions—let alone planetary mass objects. The discovery of any such objects in this annulus could provide new insights into the planetary companions of HR 8799.

5. CONCLUSIONS

We have made the first direct comparison of newly WiFi ADI reduced archival Gemini AO images to archival HST/NICMOS coronagraphic images. In both sets of images, two faint wide companions were detected. With nine years between these epochs, we can accurately assess the proper motion nature of each companion. We find that both objects are unbound to HR 8799 and are background. In this paper, our major conclusions are as follows.

1. We estimate that no bound companions of $H < 22$ mag exist from $\sim 5^\prime$ to $15^\prime$ for HR 8799A.
2. Any unseen scattered giant extrasolar planets in the HR 8799 system are $> 600$ AU and/or less than $\sim 3 M_{\text{Jup}}$ in mass.

3. The residuals in the current published astrometry of HR 8799b’s orbit are not explained by forcing HR 8799b to be a background object at $> 100$ pc.
4. While we identify no clearly bound companions to HR 8799A in our images (beyond the extrasolar planet HR 8799b), our manual search of the POSS images found one object at $4^\prime0$ separation which merits further investigation to fully rule it out as a companion.

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Facilities: Gemini, HST (NICMOS)

REFERENCES

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 2002, A&A, 382, 563
Biller, B. A., & Close, L. M. 2007, ApJ, 669, L41
Burrows, A., Sudarsky, D., & Lunine, J. I. 2003, ApJ, 569, 587
Chauvin, G., et al. 2005, A&A, 438, L29
Close, L. M., Richer, H. B., & Crabtree, D. R. 1990, AJ, 100, 1968
Close, L. M., et al. 2002, ApJ, 567, 53
Close, L. M., et al. 2003, ApJ, 587, 407
Close, L. M., et al. 2007a, ApJ, 660, 1492
Close, L. M., et al. 2007b, ApJ, 660, 736
Dodson-Robinson, S. E., et al. 2009, ApJ, 707, 79
Fabrycky, D., & Murray-Clay, R. 2008, arXiv:0812.0011v1
Fortney, J. J., Marley, M. S., Saumon, D., & Lodders, K. 2008, 683, 110
Fukugawa, M., et al. 2009, ApJ, 696, L1
Gould, A. 2003, AJ, 126, 472
Gozdziewski, K., & Migaszewski, C. 2009, MNRAS, 397, L16
Jaschek, C., & Valbousquet, A. 1993, A&A, 275, 472
Jordi, K., Grebel, E. K., & Ammon, K. 2006, A&A, 460, 339
Kratter, K., et al. 2009, arXiv:0909.2644
Laflerriere, D., et al. 2007a, ApJ, 670, 1367
Laflerriere, D., et al. 2007b, ApJ, 660, 770
Laflerriere, D., et al. 2009, ApJ, 694, L148
Lepine, S., & Shara, M. M. 2005, AJ, 129, 1483
Levine, S. 2005, AJ, 130, 319
Lowrance, P., et al. 2005, ApJ, 130, 1845
Marois, C., et al. 2006, ApJ, 641, 556
Marois, C., et al. 2008, Science, 322, 1348
Monet, D. G., et al. 2003, AJ, 125, 984
Munn, J. A., et al. 2004, AJ, 127, 3034
Neuhauser, R., et al. 2005, A&A, 435, L13
Nielsen, E. L., & Close, L. M. 2009, ApJ, in press (arXiv:0909.4531)
Nielsen, E. L., Close, L. M., Biller, B. A., Masciadri, E., & Lenzen, R. 2008, ApJ, 674, 466
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Scharf, C., & Menou, K. 2009, ApJ, 693, L113
Su, K., et al. 2009, ApJ, 705, 314
Veiras, D., et al. 2009, ApJ, 696, 1600
Zacharias, N., et al. 2004, BAAS, 36, 1418