DISCOVERY AND CHARACTERIZATION OF A FAINT STELLAR COMPANION TO THE A3V STAR ζ VIRGINIS

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ABSTRACT

Through the combination of high-order Adaptive Optics and coronagraphy, we report the discovery of a faint stellar companion to the A3V star ζ Virginis. This companion is ~7 magnitudes fainter than its host star in the H-band, and infrared imaging spanning 4.75 years over five epochs indicates this companion has common proper motion with its host star. Using evolutionary models, we estimate its mass to be 0.168\(^{+0.012}_{-0.016}\) \(M_\odot\), giving a mass ratio for this system \(q = 0.082^{+0.007}_{-0.008}\). Assuming the two objects are coeval, this mass suggests a M4V-M7V spectral type for the companion, which is confirmed through integral field spectroscopic measurements. We see clear evidence for orbital motion from this companion and are able to constrain the semi-major axis to be \(\gtrsim 24.9\) AU, the period \(\gtrsim 124\) yrs, and eccentricity \(\gtrsim 0.16\). Multiplicity studies of higher mass stars are relatively rare, and binary companions such as this one at the extreme low end of the mass ratio distribution are useful additions to surveys incomplete at such a low mass ratio. Moreover, the frequency of binary companions can help to discriminate between binary formation scenarios that predict an abundance of low-mass companions forming from the early fragmentation of a massive circumstellar disk. A system such as this may provide insight into the anomalous X-ray emission from A stars, hypothesized to be from unseen late-type stellar companions. Indeed, we calculate that the presence of this M-dwarf companion easily accounts for the X-ray emission from this star detected by ROSAT.

Subject headings: instrumentation: adaptive optics — methods: data analysis — stars: individual (HIP66249, HR5107) techniques: image processing — planet occurrence around A-type stars is twice that of solar-mass stars. In addition to planetary-mass companions, the frequency and mass ratio distributions of stellar-mass companions to nearly A stars can help constrain binary formation scenarios—such as models based on the more massive primary star dynamically capturing a lower mass companion (McDonald & Clarke 1993), or a picture relying on initial fragmentation within a protostellar cloud, e.g. Burkert & Bodenheimer (1996). Although some multiplicity studies of A and B stars have been conducted—e.g. the Shapley & Tokovinin (2002) and Kouwenhoven et al. (2005) surveys of Sco OB2—a comprehensive statistical picture of multiplicity around these massive stars, based on both cluster and field objects, has yet to emerge. Observations of massive, early-type stars may serve as important boundary-type systems, to which models of formation must conform. Specifically, an abundance of brown dwarf/M-dwarf companions to A stars would lend support to recent models describing the formation of these objects through the fragmentation of an initially massive circumstellar disk (Kratter et al. 2009; Stamatellos & Whitworth 2009).

Moreover, the frequency of stellar companions to A-stars may be related to their anomalous source of X-rays. Since A-stars have shallow or non-existent convective regions in their envelopes, they lack a significant dynamo effect, and can be expected to display negligible X-ray emission. Meanwhile, M dwarfs are well known sources of X-rays (Fleming et al. 1993; Schmitt et al. 1998).

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TABLE 1

| Parameter                      | Value |
|--------------------------------|-------|
| Identifiers                    | HIP66249, HR5107, HD118998 |
| Spectral Typea                 | A3V   |
| V magnitudeb                   | 3.40  |
| Parallax (mas)c                | 44.55±0.90 |
| RA, Dec Proper Motion (mas yr^{-1})d | -278.89±0.83, 48.56±0.71 |
| Radial Velocity (km s^{-1})e   | -13.2±0.3 |

a Crow et al. (2003)
Hofflet & Jaschek (1983)
Perryman et al. (1997)
Perryman et al. (1999)

b Abt & Biggs (1972)
Lagrange et al. (2009)

c Schröder & Schmitt (2007) find that the majority of nearby X-ray emitting A-stars have some evidence of possessing low-mass companions, likely responsible for the X-ray emission. Moreover, Zimmerman et al. (2010) have recently discovered a mid-M dwarf companion to the nearby A-star Alcor, a ROSAT source.

1. Previous Studies of ζ Virginis

The star ζ ("Zeta") Virginis (HIP66249, A3V, V=3.40—See Table 1, hereafter ζ Vir), is a target in our on-going high-contrast imaging program (Oppenheimer et al. 2004; Sivaramakrishnan et al. 2007; Hinkley et al. 2008). This nearby (22.45 pc) star has a radial velocity of -13.2 km s^{-1}.

2. Observations

We have imaged the ζ Vir system using two observing programs, each with different instruments: A coronagraph working together with an infrared camera, and a newly commissioned coronagraph which employs an IFS as the primary science camera. We describe each observing program below.

2.1. "The Lyot Project", a Coronagraphic Imager at AEOS

The first instrument, "The Lyot Project" (Oppenheimer et al. 2004; Sivaramakrishnan et al. 2007) was a diffraction-limited classical Lyot coronagraph (Lyot 1939; Sivaramakrishnan et al. 2001) working with the Adaptive Optics (hereafter "AO") system on the 3.63 m AEOS telescope on Haleakala, Hawaii (Roberts & Neyman 2002). Our images were gathered using "Kermit," an infrared camera (Perrin et al. 2003), with a 13.5 mas pixel^{-1} plate scale, and differential polarimetry mode for detection of diffuse circumstellar material (Hinkley et al. 2009). Images of ζ Vir in J, H, and K-bands were obtained using this instrument over three epochs spanning three years as listed in Table 2. Our coronagraph used a focal plane mask with a 455 mas diameter (4.9λ/D at H-band), as well as its own internal tip/tilt system. Images in the J, H, and K-bands were obtained during the second and third epochs, while only H-band was obtained on the first. To calibrate our photometry, we also obtained 1 s unocculted images in addition to the coronagraphically occulted images. In this setup, the target is more than 1" away from our occulting mask. The raw data images, both occulted and unocculted, required a mix of both traditional data reduction steps (e.g. dark current subtraction, bad-pixel masking, flat-field correction) as well as some techniques customized for the infrared camera. More details on the data reduction are given in Soummer et al. (2006) and Digby et al. (2006).

2.2. "Project 1640," a coronagraphic Integral Field Spectrograph at Palomar

The second instrument used to image the ζ Vir system is a new instrument (Hinkley et al. 2008) recently commissioned on the 200-in Hale Telescope at Palomar Observatory. This instrument, termed "Project 1640," is a coronagraph integrated with an integral field spectrograph (IFS) spanning the J and H-bands (1.05μm - 1.75μm). The IFS+Coronagraph package is mounted on the Palomar AO system (Dekany et al. 1998), which in turn is mounted at the Cassegrain focus of the Hale Telescope. The coronagraph is an Apodized-Pupil Lyot coronagraph (APLC) (Soummer 2005), an improvement of the classical Lyot coronagraph (Sivaramakrishnan et al. 2001). This coronagraph uses a 370 mas diameter (5.37λ/D at H-band) focal plane mask. The IFS, or hyper-spectral imager, is a micro lens-based spectrograph which can simultaneously obtain 4 × 10^4 spectra across our 4" × 4" field of view. Each microlens subtends 19.2
mas on the sky and a dispersing prism provides a spectral resolution ($\lambda/\Delta\lambda$)~32.

The IFS focal plane consists of $4 \times 10^4$ spectra that are formed by dispersing the pupil images created by each microlens. To build a data cube, the data pipeline uses a library of images made in the laboratory with a tunable laser, which spans the operating wavelength band of the instrument. Each image contains the response of the IFS to laser emission at a specific wavelength—a matrix of point spread functions. Each laser reference image is effectively a key showing what regions of the $4 \times 10^4$ spectra landing on the detector correspond to a given central wavelength. Each laser reference image is cross correlated with the focal plane spectra to extract each wavelength channel.

The pixel scales for each instrument were calculated at by imaging four binary stars (HIP107354, HIP171, HIP88745, and WDS11182+3132) with high quality or- at by imaging four binary stars (HIP107354, HIP171, HIP88745, and WDS11182+3132) with high quality orbits with small astrometric residuals (Hartkopf et al. 2001). The pixel scale is calculated by performing a least squares fit between these predicted separations and the pixel separation in our data.

The astrometric measurements for the primary/companion separation are presented in Table 2. For the first and third epochs, the astrometric positions of the two stars were obtained from images in which the primary star was occulted. In these cases, a centroid of the two stars were obtained from images in which the host star, is apparent at the bottom left of the image. Instead, we report a $\sim 200$ mas southwesterly change in the position of the companion (see Figure 2) relative to the host star. Since the relative separation between the host star and the companion is far less than the ~1.35" change in separation if the two were not mutually bound, we are confident that these two objects share common proper motion. Moreover, this westerly change reflects the orbital motion of $\zeta$ Vir B over the 4.75 year observing baseline.

## 3. THE COMPANION

Here we report the discovery of a faint stellar companion to $\zeta$ Vir, hereafter $\zeta$ Vir B. The discovery image is shown in Figure 1. To our knowledge, the existence of this companion has not been reported previously.

### 3.1. Common Proper Motion Analysis

The astrometric measurements for the primary/companion separation are presented in Table 2. For the first and third epochs, the astrometric positions of the two stars were obtained from images in which the primary star was occulted. In these cases, a centroid of each PSF was calculated as part of a best fit radial profile measurement. With coronagraphic imaging, the exact position of the occulted star is difficult to determine. The uncertainty can be estimated using binary stars, in which one of the binary members is occulted (Digby et al. 2006). For all but the first epoch, we used a physical mask with a superimposed grid (Sivaramakrishnan & Oppenheimer 2000), which produces fiducial reference spots indicating the position of the host star to within $\sim 10$ mas. The second, fourth and fifth epochs contained fully unocculted data with sufficiently high signal-to-noise to measure the position of both the primary and the companion. $\zeta$ Vir A, listed as a high-proper motion star, has a proper motion of 283 mas yr$^{-1}$ (Perryman et al. 1997). If these two objects were not associated with each other, we could expect a $\sim 1.35"$ change in separation over the 4.75 year course of observations. Instead, we report a $\sim 200$ mas'

### 3.2. Photometry

Aperture photometry of the companion was performed on images from the Lyot Project in which $\zeta$ Vir was occulted behind our 455 mas occulting mask. A faint stellar companion, $\zeta$ Vir B, 7 magnitudes fainter than the host star and sharing common proper motion with the host star, is apparent at the bottom left of the image.
Fig. 2.— The offset positions of ζ Vir B relative to the host star. The position of the host star is marked with the ⋆ symbol. The inset portion of the plot shows the positions of the stellar companion over the 4.75 years of observations presented in this paper. The error bars incorporate the uncertainties in the radial separation and the position angle. The vector labelled “μ” at the upper right shows the magnitude and direction of the proper motion of the ζ Vir system over the 4.75 year duration of these observations (~1325 mas/yr, 230.66 mas/yr).

3.3. Spectroscopy

Integrating an IFS into more conventional high-contrast imaging techniques can provide significantly more information on objects in close vicinity to their host star (Sparks & Ford 2002; Berton et al. 2006; McElwain et al. 2007). Normally, when spectra are unavailable, parameters such as mass, spectral type, and age must be derived by combining broadband photometry with model predictions. Such models can be problematic at very young ages (Stassun et al. 2006; Allers et al. 2007).

Observations with our IFS at Palomar Observatory (Hinkley et al. 2008) allowed us to obtain the spectrum of ζ Vir B shown in Figure 3. Each point in the spectrum of ζ Vir B was calculated by performing aperture photometry on each image in a data cube. Examples of such images taken from a data cube are shown in Figure 4. The photometry was obtained using a circular aperture such that the second Airy ring of the Point Spread Function was enclosed at each wavelength in the data cube. A median background sky value was calculated in a 40 mas wide annulus, just outside the photometric aperture, and subtracted from the target counts. Each flux value for ζ Vir B shown in Figure 3 is a median of five data points taken from five data cubes of ζ Vir B, and the error bars show the 1σ spread of these five values. The spectrum was calibrated using a reference star (HIP 56809, G0V, V = 6.44) by comparing the measured counts of the reference star with a template G0V star (HD 109358, G0V, V = 4.26) taken from the IRTF spectral Library (Cushing et al. 2005; Rayner et al. 2009) to derive a spectrograph response function.

Table 3: Photometry for ζ Virginis B

| Band | Apparent Magnitude | Absolute Magnitude |
|------|--------------------|--------------------|
| J    | 10.75 ± 0.06       | 8.99 ± 0.06        |
| H    | 10.17 ± 0.14       | 8.41 ± 0.14        |
| K    | 9.90 ± 0.17        | 8.14 ± 0.17        |

The spectra shown in Figure 3 has had this response correction applied to it. We have excluded the data points in the vicinity of the water absorption band between ~1.35 μm and ~1.5μm, since the degree of water absorption present in the calibrator star was sufficiently different from that present in the ζ Vir observations. Also shown in the figure are template spectra for an M2V through M7V star taken from the IRTF spectral Library. The extracted spectrum for ζ Vir B is most consistent with the M4V - M7V spectral types.

Fig. 3.— The J and H-band spectrum of ζ Vir B obtained with our IFS and coronagraph at Palomar (Hinkley et al. 2008). Also shown are template spectra for M2V through M7V stars taken from the IRTF spectral Library (Cushing et al. 2005; Rayner et al. 2009). The water band data points between ~1.35 and ~1.5μm have been excluded due to the variation of this band between observations of ζ Vir and our calibrator star.

4. Analysis

4.1. Mass and Age of ζ Vir A

Although Hoffleit & Jaschek (1982) list ζ Vir as a possible member of the Hyades moving group, several lines of evidence suggest simply assigning the system the age of the Hyades cluster is not rational. Indeed, using criteria based on mass distribution and metallicity, Famaey et al. (2007) question whether most members of the Hyades Moving Group are actually evaporated mem-
mass values are slightly lower than the model. The Henry & McCarthy (1993) and Delfosse et al. (2000) mass-luminosity relations give an overall derived mass for \( \zeta \) Vir A of 2.041 \pm 0.024 \( M_\odot \). We take this value as the final mass for \( \zeta \) Vir A and \( \zeta \) Vir B, respectively. In this analysis we have assumed a mass of 2.041 \pm 0.024 \( M_\odot \) for \( \zeta \) Vir A and \( 0.168 \pm 0.016 \) \( M_\odot \) for \( \zeta \) Vir B, respectively.

4.2. Mass and Age of \( \zeta \) Vir B

We use the models of Baraffe et al. (2003) to derive a mass for \( \zeta \) Vir B assuming the age of 505 Myr. In Figure 5 (right panel) we show plots of the \( J \), \( H \), and \( K \)-band absolute magnitudes for a range of companion masses calculated from these models. As with the case of \( \zeta \) Vir A, the uncertainty in the photometry of this object has very little effect on the derived mass of the companion. Together these values give an overall derived mass of \( 0.168 \pm 0.016 \) \( M_\odot \). We take this value as the final derived mass for \( \zeta \) Vir B.

To check the validity of this model-based mass estimate, we compare this value with empirically derived mass-luminosity relations given in Henry & McCarthy (1993) and Delfosse et al. (2000). Using the \( J \), \( H \), and \( K \) magnitudes, these two works predict values of 0.152 \pm 0.009 \( M_\odot \) and 0.166 \pm 0.004 \( M_\odot \) (see Table A), consistent with a mid-M spectral type for a main sequence star at these ages (Reid et al. 1995; Hawley et al. 1996), and consistent with the spectral determination derived previously. The Henry & McCarthy (1993) and Delfosse et al. (2000) mass values are slightly lower than the model-based 0.168 \( M_\odot \) value given by the Baraffe et al. (2003) models, but are still consistent with a mid-M spectral type for \( \zeta \) Vir B. Using the range of primary star masses derived above gives this system a mass ratio of \( q = 0.082^{+0.007}_{-0.008} \).

4.3. Orbital Analysis

Given the relatively short span (4.75 years) of the observations of \( \zeta \) Vir B (see Figure 2), fitting an orbital model to the data is premature. However, we may borrow an analysis used by Golimowski et al. (1998) to constrain the eccentricity, \( e \), and semi-major axis, \( a \), of \( \zeta \) Vir B using our astrometry in the two-dimensional plane of the sky, combined with Kepler’s Laws. We refer the reader to Golimowski et al. (1998) for a full explanation. Over our 4.75 year time baseline, we calculate a velocity of \( -1.139 \) AU yr\(^{-1} \) in the westward direction, and \( 0.02 \) AU yr\(^{-1} \) in the south direction. Assuming the orbit of \( \zeta \) Vir B is bounded, and assuming a range of line-of-sight positions and velocities for \( \zeta \) Vir B, we are able to constrain \( a \) and \( e \), and we show the loci of possible values for these parameters in Figure 6. The ordinate and abscissa values show the assumed values of the line-of-sight velocity, and position, respectively. The values shown in Figure 6 indicate a \( a \gtrsim 24.9 \) AU and \( e \gtrsim 0.16 \), from the semi-major axis constraint, we can constrain the period \( P = (4\pi^2a^3/\mu)^{1/2} \) to be \( \gtrsim 124 \) yrs, where \( \mu = G(m_1 + m_2) \). In this analysis we have assumed a mass of \( m_1 = 2.04 M_\odot \) (see Figure 5) and \( m_2 = 0.168 M_\odot \) for \( \zeta \) Vir A and \( \zeta \) Vir B, respectively.

5. DISCUSSION

Assuming a mass of 2.041 \pm 0.024 \( M_\odot \) for \( \zeta \) Vir A gives this newly discovered binary system a mass ratio of \( q = 0.082^{+0.007}_{-0.008} \). Although numerous low-mass companions have been detected around \( \sim 1 M_\odot \) stars, this system is of particular interest given that it orbits a primary star of \( \sim 2 M_\odot \). The \( q \) distributions for primaries in the mid and low mass stellar regimes have been well studied, but comprehensive binary statistics for A stars are incompletely surveyed. The mass ratio distribution for the mid and lower mass ranges show fairly
Fig. 5.— The left hand panel shows the luminosity-mass relation for the host star, ζ Vir A as calculated by Siess et al. (2000) for a 505 Myr system. We use absolute $V$-magnitude in lieu of total luminosity. The vertical extent of the box indicates the $V$-band photometric uncertainty ($M_V = 1.64 \pm 0.06$) for ζ Vir A. This defines an allowable region for the mass for the A3V host star to be $2.041 \pm 0.024 \, M_{\odot}$.

The right panel shows evolutionary models for low-mass stars taken from Baraffe et al. (2003) for the $J$, $H$, and $K$-bands. As with the case for ζ Vir A, the vertical extent of each box indicates the photometric uncertainty at each band. These three bandpass values gives an overall value of $0.168^{+0.012}_{-0.016} \, M_{\odot}$ for ζ Vir B.

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### Table 4

| Model                  | Method                        | $J$-band  | $H$-band  | $K$-band  | Median ± 1σ     |
|------------------------|-------------------------------|-----------|-----------|-----------|-----------------|
| Henry & McCarthy (1993)| Mass-Luminosity (Empirical)   | 0.136 M⊙ | 0.152 M⊙ | 0.152 M⊙ | $0.152 \pm 0.009 \, M_{\odot}$ |
| Baraffe et al. (2003)  | (505 Myr) Evolutionary (Theoretical) | 0.168 M⊙ | 0.169 M⊙ | 0.167 M⊙ | $0.168 \pm 0.001 \, M_{\odot}$ |
| Delbosse et al. (2000) | Mass-Luminosity (Empirical)   | 0.170 M⊙ | 0.166 M⊙ | 0.163 M⊙ | $0.166 \pm 0.004 \, M_{\odot}$ |

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clear trends with mass. Namely, Burgasser et al. (2007) discusses that very low mass binaries have mass ratios that are skewed towards unity. Studies using a complete sample of stars between 0.6 - 0.85 M⊙ (Mazeh et al. 2003), as well as M-dwarf surveys (Fischer & Marcy 1992; Reid & Gizis 1997), find a significantly flat distribution of mass ratios. In the same vein, Kraus et al. (2008), used a sample of 82 young stars of GKM type in the Upper Sco star forming region and found a distribution of mass ratios not significantly different from a constant distribution, i.e. not significantly biased towards having low mass companions. Towards higher masses, Duquennoy & Mayor (1991) find that F and G type stars have a broad range of mass ratios, but with a slight increase towards small secondary masses. Finally, at the higher mass end, Shatsky & Tokovinin (2002) and Kouwenhoven et al. (2005) have performed a survey of A and B-stars in the Sco OB2 association, finding a high rate of binarity.

Similarly, many studies show a positive correlation between the distribution of binary separations and the mass of the system. The Duquennoy & Mayor (1991) sample of solar mass stars show a mean separation of ~30 AU. At lower masses, the Fischer & Marcy (1992) survey (largely M dwarfs within 8 pc) and Reid & Gizis (1997) surveys (M dwarfs within 20 pc) find mean separations between 4 and 30 AU. Continuing towards lower masses, low mass M dwarfs and brown dwarfs as discussed in Burgasser et al. (2007), have notably smaller mean separations (~4 AU), with maximum separations ~20 AU.

Kouwenhoven et al. (2003) and Shatsky & Tokovinin (2002) have undertaken the first steps towards a comprehensive study of the multiplicity of A stars. Our work aims to aid in that effort. The value of the current study lies in the ability to obtain a spectrum which determines the spectral type, a tight constraint on the secondary mass, and a constrained orbit.

Our finding may also be useful for studies of the anomalous X-ray emission from A stars. Unseen late-type companions to A stars have been hypothesized to be the source of their anomalous X-ray emission. Indeed, the presence of the M-dwarf companion in this system can easily account for the X-ray flux detected by ROSAT. For a $0.168 \, M_{\odot}$ star at 505 Myr, the Baraffe et al. (2003) model...
The contours for the left plot are 27, 35, 60, 100, 160, and 300 AU. The right hand plot shows eccentricity contours equal to 0.25, 0.50, 0.60, 0.75, and 0.90. This constrains the semi-major axis to be $\gtrsim 24.9$ AU (and hence the period to be $\gtrsim 124$ yrs), and eccentricity $\gtrsim 0.16$.

(2003) evolutionary tracks predict a luminosity of $L_{\text{bol}} \approx 2 \times 10^{31}$ erg s$^{-1}$. And assuming that the X-ray luminosity $L_x = 1.07 \times 10^{28}$ erg s$^{-1}$ noted by [Huensch et al. (1998)] is due completely to the companion, this predicts a log($L_x/L_{\text{bol}}$) value of -3.3, quite typical for a young mid M dwarf (See [Fleming et al. (1993), especially their Figure 3]). Recently, [Zimmerman et al. (2010)] have reported the presence of a mid-M dwarf bound to the star Alcor. More complete high-contrast surveys for companions surrounding an ensemble of A stars will allow researchers to begin to address the issue of the anomalous X-ray emission in a statistically robust manner.

An abundance of M-dwarf companions in configurations like this also may lend support to models of binary formation based on fragmentation of a massive circumstellar disk. As [Kratter et al. (2009)] point out, massive stars with their presumably massive circumstellar disks and correspondingly high mass infall rates provide an environment conducive for the formation of disk instabilities and fragmentation. Indeed, such a mechanism is more likely for disks surrounding stars more massive than 1-2M$_\odot$ [Krumholz et al. (2007), Kratter et al. (2008)]. If indeed this fragmentation is a prominent mechanism for the formation of binary companions [Stamatellos & Whitworth (2009)], the abundance of low mass companions (brown dwarfs and M-dwarfs) should be more frequent around more massive stars.

6. SUMMARY

We report the discovery of a low-mass, M4V-M7V stellar companion to the star $\zeta$ Vir. This object clearly shares common proper motion with its host star, and we derive a mass of $0.168^{+0.012}_{-0.016}$ M$_\odot$, corresponding to a mass ratio $q = 0.082^{+0.007}_{-0.008}$. Our broad-band photometry and spectroscopy are consistent with an mid-M spectral type. Although numerous low-mass companions have been identified around $\sim 1$ M$_\odot$ systems, this object is significant given its membership in a $\sim 2$ M$_\odot$ system. Characterization of more systems like this are important for identifying the anomalous source of X-rays from A stars as well as constraining possible modes of formation of stellar companions through the fragmentation of massive circumstellar disks.

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A Faint Companion to the Star ζ Vir

Perryman, M. A. C., Brown, A. G. A., Lebreton, Y., Gomez, A., Turon, C., de Strobel, G. C., Mermilliod, J. C., Robichon, N., Kovalevsky, J., & Crifo, F. 1998, A&A, 331, 81
Perryman, M. A. C., Lindegren, L., Kovalevsky, J., Hoeg, E., Bastian, U., Bernacca, P. L., Crézé, M., Donati, F., Grenon, M., van Leeuwen, F., van der Marel, H., Mignard, F., Murray, C. A., Le Poole, R. S., Schrijver, H., Turon, C., Arenou, F., Froeschlé, M., & Petersen, C. S. 1997, A&A, 323, L49
Rayner, J. T., Cushing, M. C., & Vacca, W. D. 2009, ArXiv e-prints
Reid, I. N., & Gizis, J. E. 1997, AJ, 113, 2246
Reid, I. N., Hawley, S. L., & Gizis, J. E. 1995, AJ, 110, 1838
Rieke, G. H., Su, K. Y. L., Stansberry, J. A., Trilling, D., Bryden, G., Muzerolle, J., White, B., Gorlova, N., Young, E. T., Beichman, C. A., Stapelfeldt, K. R., & Hines, D. C. 2005, ApJ, 620, 1010
Roberts, L. C., & Neyman, C. R. 2002, PASP, 114, 1260
Schmitt, J. H. M. M., Golub, L., Harnden, Jr., F. R., Maxson, C. W., Rosner, R., & Vaiana, G. S. 1985, ApJ, 290, 307
Schröder, C., & Schmitt, J. H. M. M. 2007, A&A, 475, 677
Shatsky, N., & Tokovinin, A. 2002, A&A, 382, 92
Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593
Sivaramakrishnan, A., Koreas, C. D., Makidon, R. B., Berkefeld, T., & Kuchner, M. J. 2001, ApJ, 552, 397
Sivaramakrishnan, A., & Oppenheimer, B. R. 2006, ApJ, 647, 620
Sivaramakrishnan, A., Oppenheimer, B. R., Hinkley, S., Brenner, D., Soummer, R., Mey, J. L., Lloyd, J. P., Perrin, M. D., Graham, J. R., Makidon, R. B., Roberts, L. C., & Kuhn, J. R. 2007, Comptes Rendus Physique, 8, 355
Smith, B. A., & Terrile, R. J. 1984, Science, 226, 1421
Soummer, R. 2005, ApJ, 618, L161
Soummer, R., Oppenheimer, B. R., Hinkley, S., Sivaramakrishnan, A., Makidon, R. B., Digby, A. P., Brenner, D., Kuhn, J. R., Perrin, M. D., Roberts, L. C., & Kratter, K. 2006, in EAS Publications Series, ed. C. Aime & M. Cariblet Sparks, W. B., & Ford, H. C. 2002, ApJ, 578, 543
Stamatellos, D., & Whitworth, A. P. 2009, MNRAS, 392, 413
Stassun, K. G., Mathieu, R. D., & Valenti, J. A. 2006, Nature, 440, 311
Zimmerman, N., Oppenheimer, B. R., Hinkley, S., Brenner, D., Parry, I. R., Sivaramakrishnan, A., Hillenbrand, L., Beichman, C., Crepp, J. R., Vasisht, G., Roberts, L. C., Burress, R., King, D. L., Soummer, R., Dekany, R., Shao, M., Bouchez, A., Roberts, J. E., & Hunt, S. 2010, ApJ, 709, 733