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Direct imaging of the young spectroscopic binary HD 160934⋆ (Research Note)

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ABSTRACT

Context. Members of nearby moving groups are promising candidates for the detection of stellar or substellar companions by direct imaging. Mass estimates and magnitude measurements of detected companions to young stars are valuable input data to facilitate the refinement of existing pre-main-sequence stellar models. In this paper we report on our detection of a close companion to HD 160934, a young active star, SB1 spectroscopic binary, and suggested member of the AB Doradus moving group.

Aims. We obtained high angular resolution images of nearby young stars, searching for close companions. In the case of HD 160934, direct imaging was combined with unresolved photometry to derive mass estimates.

Methods. High angular resolution was achieved by means of the so-called "Lucky Imaging" technique, allowing direct imaging close to the diffraction limit in the SDSS z' band with a 2.2 m telescope. Our results are combined with pre-discovery HST archive data, own $UBV(RI)_C$ broadband photometry, published JHK magnitudes, and available radial velocity measurements to constrain the physical properties of the HD 160934 close binary.

Results. At an assumed age of ∼80 Myr, we derive mass estimates of 0.69 $M_\odot$ and 0.57 $M_\odot$, respectively, for HD 160934 and its close companion. We suggest that the direct detection may be identical to the spectroscopically discovered companion, leading to a period estimate of ∼8.5 years and a semimajor axis of $a \approx 4.5$ AU.

Key words. instrumentation: high angular resolution – binaries: spectroscopic – binaries: visual – stars: fundamental parameters – stars: individual: HD 160934

1. Introduction

HD 160934 (= HIP 86346) is a young late-type star with a spectral type of K7 to M0 (Reid et al. 1995; Zuckerman et al. 2004a) at a distance of ≈24.5 pc (Perryman et al. 1997). It is chromospherically active (Mulliss & Bopp 1994) with prominent EUV (e.g., Pounds et al. 1993) as well as X-ray emission with an X-ray luminosity of $L_X = 3.4 \times 10^{22}$ W (Hünsch et al. 1999). The activity can also be traced in the Hα line, which is seen in emission with an equivalent width between −0.09 and −0.13 nm (Mulliss & Bopp 1994; Gizis et al. 2002; Zuckerman et al. 2004a). The detection of the Li 6708 Å line with an equivalent width of 40 mÅ (Zuckerman et al. 2004a) gives further evidence that HD 160934 is a relatively young star. These youth indicators combined with the 3d space motion led Zuckerman et al. (2004a,b) and Lopez-Santiago et al. (2006) to suggest that HD 160934 might be a member of the ≈50 Myr old AB Dor moving group.

Because of its proximity to the Sun and its young age, HD 160934 is a good candidate for the direct detection of substellar, or even planetary mass companions. McCarthy & Zuckerman (2004) report that no brown dwarf companion could be found at projected separations larger than 75 AU as a result of a near infrared coronagraphic study carried out at the Keck observatory. Using HST/NICMOS in coronagraphic mode, Lowrance et al. (2005) report the detection of a possible wide companion to HD 160934 at a projected separation of ≈8.″7 (corresponding to ≈210 AU) and at a position angle of ≈235°. The brightness difference between the companion candidate, designated HD 160934 B, and HD 160934 A is $\Delta H = 9.2$ mag. Under the assumption that HD 160934 B constitutes a physical companion to HD 160934, Lowrance et al. (2005) derive a mass estimate of ≈0.15 $M_\odot$ for this companion.

By combining 37 radial velocity measurements, Gálvez et al. (2006) were able to identify HD 160934 as a spectroscopic SB1 binary and suggested a period of $P = 6246.2318$ days, a high eccentricity of $e = 0.8028$, and a spectral type of M2−M3V for the close companion, so that HD 160934 may be actually at least a triple system.

In July 2006, we started a high angular resolution survey for close stellar and substellar companions to young nearby stars, taking advantage of the diffraction limited performance provided by using "Lucky Imaging" at the Calar Alto 2.2 m telescope. The absence of a coronagraphic mask in our set-up, and the fact that the diffraction limit of a 2.2 m telescope at the effective observation wavelength of ≈900 nm corresponds to an angular resolution of ≈0.″1 means that our survey is sensitive to companions at close separations. In this Research Note we report on the first results of the survey, namely the direct imaging of HD 160934 and a close companion. We summarise the available photometric measurements, give new $UBV(RI)_Cz'$ magnitudes, and discuss

⋆ Based on observations collected at the Centro Astronómico Hispano Alemán (CAHA) at Calar Alto, operated jointly by the Max-Planck-Institut für Astronomie and the Instituto de Astrofísica de Andalucía (CSIC). Based on observations obtained with MPIA's Königstuhl mountain 70 cm telescope.

the possibility that the spectroscopic and our direct detection refer to the same companion.

2. Observations and data reduction

2.1. Direct imaging with AstraLux at the Calar Alto 2.2 m telescope

Observations at the Calar Alto 2.2 m telescope were obtained with the new "Lucky Imaging" instrument AstraLux. The Lucky Imaging technique is based on the fact that in a large set of ground based short exposure images at least a small fraction will be relatively unaffected by atmospheric turbulence. By finding and using only these high-quality images, one is able to obtain diffraction limited images from the ground without the need of adaptive optics (Baldwin et al. 2001; Tubbs et al. 2002; Law et al. 2006).

The AstraLux instrument basically consists of an electron multiplying, thinned and back-illuminated CCD, which is operated in frame transfer mode and capable of running at a frame rate of 34 Hz when reading the full 512 × 512 pixel frame. The camera is mounted at the Cassegrain focus of the telescope behind a simple Barlow lens assembly, which changes the focal ratio from $f/8$ to $f/32$ in order to get an image scale of 46.6 mas/pixel at a physical pixel size of $16 \times 16\ \mu m^2$. This provides Nyquist sampling at $\lambda \approx 1\ \mu$m, and slightly undersamples the theoretical point spread function (PSF) at the typical observation wavelengths of 700−950 nm. With the exception of the mount needed to attach the camera to the telescope, all components were bought off-the-shelf, making AstraLux a simple and cost-effective instrument, taking less than six months from the first idea to first light.

HD 160934 was observed as part of a larger sample of nearby young stars on July 8, 2006 under good atmospheric conditions with a photometric sky and a V-band seeing around 0.″8. The raw data for HD 160934 consists of two FITS cubes of 15 000 frames with 15 ms exposure time each. We used only a 256 × 256 pixel subarray of the chip, leading to a frame rate of ≈65 Hz. The target was observed through two different filters, namely Schott RG780 and RG830 longpass filters, the latter roughly matching the SDSS z'-band (for the definition of the SDSS passbands, see Fukugita et al. 1996).

The best images were selected by calculating the ratio between peak flux and total flux of the observed star, referred to a circular aperture centered on the brightest pixel. This number is linearly related to the Strehl number – at least in the high-quality images we are interested in – and a reliable measure to find the frames least affected by atmospheric turbulence.

The final image was constructed by combining the best 2% of all images using the Drizzle algorithm (Fruchter & Hook 2002), corresponding to a total integration time of 4.5 s. The images were two times oversampled during drizzling, leading to a final pixel scale of 23.3 mas/px. The total time needed for data acquisition amounts to about 5 min per filter, including instrumental overheads, and approximately the same time is needed for data reduction. Our own version of the drizzle algorithm makes use of the fact that we do not expect any changes in image rotation or field distortion between the individual images, and thus only considers translations. This allows a fast and simple implementation, and a near real-time data reduction.

The pixel scale and image orientation were determined with a set of seven "standard binary" observations, i.e., observations of known visual binaries (chosen from the Sixth Catalog of Orbits of Visual Binary Stars, Hartkopf & Mason 2006, orbit grades 1 and 2) with angular separations between 0.″6 and 2.″8. These binaries were observed several times during the night (typically 2 standards/h) in the same manner and with the same instrumental setup as the science targets, and the final reference images were obtained using the same reduction techniques. The pixel scale and rotation angle determined using these reference images showed a high stability within 1% and 0.5°, respectively, during the whole night. Although utilizing double stars as calibrators for other double star measurements is far from optimal, we think that using a set of several stars is sufficient to determine sound upper limits of the measurement errors.

2.2. HST/NICMOS

Observations of HD 160934 with HST/NICMOS were obtained on June 30, 1998 (GO 7226, PI E. Becklin). Since the main aim of the programme was to search for faint, substellar companions, the coronagraphic mask in NIC2 was used. Because of this, the close companion to HD 160934 was not detected in the science data (see Lowrance et al. 2005). It is, however, detectable in the two acquisition frames.

The acquisition frames were obtained with the *F165M* filter and an integration time of 0.626 s. For the analysis we assumed a pixel scale of 75.10 mas/pixel. The FWHM of the PSF was around 2 pixel, corresponding to 150 mas, which is close to the diffraction limit of HST at the observing wavelength. For the second acquisition frame, taken at the beginning of a subsequent orbit, the HST guide star acquisition partially failed, resulting in a slightly trailed PSF.

Figure 1 shows a comparison of the AstraLux RG 780 and RG 830, and the NICMOS F165M images of the HD 160934 binary, while Table 1 gives the dates and details of the direct imaging observations.

The analysis of the binary properties is based on the pipeline reduced frames. Tiny Tim Version 6.3 (Krist & Hook 2004) was used to compute the theoretical PSF. In order to estimate the effect of HST "breathing" (i.e. focus changes induced by thermal expansion or shrinking of the optical train of HST), also slightly defocused PSFs were calculated and used for the binary fitting.

2.3. Fitting of binary parameters

For both data sets (AstraLux and NICMOS) a binary model (see Bouy et al. 2003) was fitted to the data in order to derive binary separation, position angle and brightness ratio. For the NICMOS data, only the first acquisition frame was used. The slightly trailed binary PSFs due to the partial guide star acquisition failure for the second HST orbit resulted in a bias in the determination of the brightness ratio using a non-trailed PSF.

While for the NICMOS data a theoretical model can serve as reference PSF for binary fitting, this is not possible for the Lucky Imaging data. Since the PSF shape depends strongly on actual seeing conditions, it is difficult to predict the theoretical PSF of a single star in the final results. Neither is there a single star available in our images, which could have served as an accurate reference PSF. We therefore decided to use a set of eight different reference PSFs, generated from observations of single stars throughout the same night, and to use the weighted average of separation, brightness ratio and position angle from all eight fit results, using the square of the residuals as weighting parameter. While the residuals vary strongly for the different reference PSFs, the resulting separations and position angles show only a small scatter. This is not the case for the measured brightness

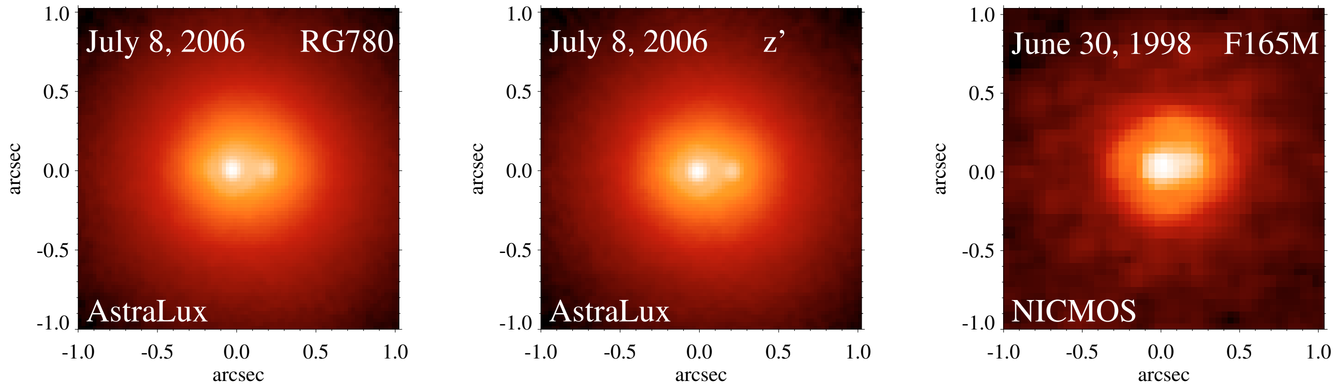

Fig. 1. AstraLux RG780, z' and NICMOS *F165M* images of the binary using a logarithmic intensity scale. The field of view is $2'' \times 2''$, and North is up and East is to the left. The binary components are clearly detectable in all three bands. Note that both the AstraLux and NICMOS images have been oversampled by a factor of 2 compared to the original instrumental pixel scale as part of the drizzle process.

Table 1. Direct imaging observing log for HD 160934.

Date	Telesc./inst.	Filter	t_{int}
June 30, 1998	HST/NIC2	*F165M*	2×0.626 s
July 8, 2006	CA 2.2 m/AstraLux	*RG780*	4.5 s[a]
July 8, 2006	CA 2.2 m/AstraLux	*RG830*	4.5 s[a]

[a] Best 2% of 15 000 frames with an individual $t_{exp} = 0.015$ s.

Table 2. Binary properties.

Date (Filter)	Separation [$''$]	PA [°]	Brightn. ratio
June 30, 1998 (*F165M*)	0.155 ± 0.001	275.5 ± 0.2	0.485 ± 0.006
July 8, 2006 (*RG830*)	0.215 ± 0.002	270.9 ± 0.3	0.329 ± 0.051

ratios – here the 1σ error of the weighted mean is ∼16%, considerably higher than for the HST-based *F165M* brightness ratio. The derived fitting results can be found in Table 2.

2.4. Unresolved photometry

Available photometry of the unresolved binary covers the wavelength range from U- to K-band. Weis (1991, 1993) has published Johnson-Kron *UBVRI* photometry. *JHK* magnitudes are contained in the 2MASS point source catalogue (Skrutskie et al. 2006). In addition, we obtained own $UBV(RI)_C$ and z' photometry, using MPIA's Königstuhl mountain 70 cm telescope on September 5th and September 13th 2006. We also performed narrowband photometry in Hα in order to derive an Hα–R color index, but calibration of this measurement proved to be rather difficult and inaccurate, probably due to the relatively wide passband of the available Hα interference filter.

During the course of the Hipparcos mission, 96 photometric measurements of HD 160934 were acquired. The lightcurve shows irregular brightness variations with semi-amplitudes of 0.05−0.1 mag on timescales on the order of few days. Further evidence for the variability of HD 160934 is given by Pandey et al. (2002) and Henry et al. (1995), suggesting amplitudes of ≈0.1 mag. While Pandey et al. find a period of 43.2 days, the observations of Henry et al. point to a much shorter value of 1.84 days with uncertainties regarding the presence of a longer period.

Table 3. Unresolved photometry of HD 160934.

Source	Filter/Color	mag		1σ
Königstuhl 70 cm	V	10.192	±	0.014
	$U-B$	0.947	±	0.008
	$B-V$	1.215	±	0.005
	$V-R_C$	0.789	±	0.004
	R_C-I_C	0.766	±	0.007
	z'	8.820	±	0.009
Weis (1991, 1993)	V	10.28	±	0.020
	$U-B$	0.95	±	0.015
	$B-V$	1.23	±	0.015
	$V-R$	0.78[a]	±	0.015
	$R-I$	0.63[a]	±	0.015
2MASS	J	7.618	±	0.024
	H	6.998	±	0.016
	K	6.812	±	0.020
Hipparcos	V	10.29		
	$B-V$	1.591	±	0.400
	$V-I_C$	2.58	±	0.91

[a] The R and I-band photometry of Weis is given in the Kron system. Using the cubic transformations given by Bessell & Weis (1987), the corresponding colors in the Cousins system are $V-R_C = 0.78$ and $R_C-I_C = 0.79$.

Table 3 summarises all available unresolved photometric measurements.

2.5. Radial velocity measurements

Radial velocity (RV) measurements of HD 160934 exist for the years 1995−2004. Gálvez et al. (2006) published an RV curve based on 38 measurements, eventually leading to the classification of HD 160934 as an SB1 spectroscopic binary with an RV amplitude of $K \approx 7.2\,\mathrm{km\,s^{-1}}$. They deduced a period of $P = 6246.2318$ days and an eccentricity of $e = 0.8028$, and derived a spectral type of M2−M3V for the companion based on their mass estimates. However, the observations cover less than one orbit and hence only one minimum of the radial velocity. In addition, the phase coverage is relatively sparse with only one single measurement for phases 0.2−0.9, so the given orbital parameters should be considered as preliminary values. While the available data certainly allows to conclude that the orbit is relatively eccentric, it is this high eccentricity which makes period estimates without better coverage of the full RV curve unreliable.

3. Physical properties of the HD 160934 binary

3.1. Common proper motion

The proper motion of the HD 160934 main component amounts to $\mu_{\rm RA} = -31.25 \pm 14.43$ mas/yr and $\mu_{\rm Dec} = 59.44 \pm 11.21$ mas/yr. In the 8 years, which passed between the NICMOS and AstraLux observations, HD 160934 moved 250 ± 115 mas to the West, and 475 ± 90 mas to the North. In the same period, the separation between HD 160934 A and c increased by ≈60 mas, and the position angle decreased by ≈5 deg (see Table 2). This gives strong evidence that both sources form indeed a physical binary.

3.2. Photometric estimates of masses and spectral types

Spectral types ranging from K7 (e.g., Reid et al. 1995) to M0 (Zuckerman et al. 2004a) have been assigned to HD 160934. While Reid et al. (1995) measured spectral indices, Zuckerman et al. (2004a) based their spectral typing on the optical $V-K$ colour of the unresolved binary.

We derived our own estimates of the spectral types and components' masses using the $V-I_{\rm C}$ colour index, the V magnitude of the unresolved system, and the SDSS z' and *F165M* magnitude differences of the components. We compared these values to the theoretical predictions based on the models of Baraffe et al. (1998, abbreviated BCAH98 in the following text) for solar metallicity low-mass stars, searching for a mass combination best fitting the available photometry. For our estimates we assumed coevality of the components. Since the published BCAH98 models do not directly predict z'-band magnitudes, we used the empirical color transforms of Jordi et al. (2006) to transform from $R_{\rm C}I_{\rm C}$ to SDSS z'. Though this seems like a crude method and calculating appropriate z'-band magnitudes from model spectra should be preferred, we think that this method is sufficient, since we are not fitting the z'-magnitudes directly, but the z'-magnitude difference between the two components instead. For components of similar spectral types this approximation is a valid way to convert between magnitude differences in the Johnson/Cousins and the SDSS photometric system.

A similar approach was taken in the case of the *F165M* magnitude differences. Since the centers of the *F165M* and H passband are nearly identical, and the passbands differ only in width, we directly compare the *F165M* magnitude difference with the H-band magnitude differences of the models. As in the case of the z'-band difference, this is a sound approximation for combinations of similar spectral types.

The BCAH98 model magnitudes were interpolated on a finer mass grid, and for each possible mass combination in the range of 0.2−1.0 $M_\odot$ the combined V magnitude, $V-I_{\rm C}$ color index, and the SDSS z' and H-band brightness ratios were computed and compared to our measurements (in the case of the V-band magnitude, the comparison was made to absolute V magnitude, based on the Hipparcos parallax). The residuals were weighted by the measurement errors, and the best fitting mass combination found by determining the global minimum of the residuals. We performed fitting with models for different ages, namely in the range of 30 to 158 Myr. Minimum residuals were obtained with the BCAH98 model for an age of 79 Myr, and the resulting mass estimates are given in Table 4, together with the effective temperatures, luminosities, and surface gravity from BCAH98.

Table 4. HD160934Ac mass estimates for an assumed age of 79 Myr.

Component	Mass [$M_\odot$]	$T_{\rm eff}$ [K]	$\log L/L_\odot$	g
A	0.69	4290	–0.83	4.60
c	0.57	3780	–1.23	4.68

Using the modelled unresolved V-magnitude, we derive a distance module of $M-m = 2.81$, corresponding to a distance of $d = 36.5$ pc or a parallax of $\pi = 27.4$ mas. Compared with the directly measured Hipparcos parallax of 40.75 ± 12.06 mas, this deviates by 1.1σ. Of course, since the Hipparcos parallax and its error were actually used in the fitting process, this photometric distance estimate is not an independent measurement and somewhat circular. However, the derived values constitute a set of physical parameters compatible to the observations within the measurement errors.

While it is tempting to believe that our findings may be sufficient to pin down not only the components' masses, but also to determine the age, it should be noted that especially the age is not very well constrained by the data. Using the BCAH98 models for 50 Myr results in nearly equally small residuals, while the components' masses would then be 0.64 and 0.77 $M_\odot$, respectively. The error of our mass estimates should therefore assumed to be in the order of 0.1 $M_\odot$. This clearly indicates that photometry-based mass estimates without independent age constraints or spectroscopically determined effective temperatures are affected by relatively high uncertainties. It should also be noted that the V magnitudes of the BCAH98 models are known to be be rather inaccurate for very-low-mass stars (e.g., Allard et al. 1997), and that this may to some extent still be the case in the 0.7 $M_\odot$ regime.

As a crosscheck, we computed the combined J, H and K magnitudes of the unresolved binary as predicted by the BCAH98 models, and compared them to the 2MASS observations given in Table 3. The model magnitudes (using $d = 36.5$ pc) are $J = 7.59$, $H = 6.99$, $K = 6.86$, which gives a maximum deviation of 2.4σ or 0.048 mag in K-band.

The derived values allow a tentative estimate of the components' spectral types, suggesting a combination of a K5 and an M0 star, which is in good agreement with the published spectral types of the unresolved binary (Reid et al. 1995; Zuckerman et al. 2004a).

3.3. Orbital parameters and comparison to RV data

Between the HST and AstraLux observations, the change in projected separation and position angle was 65 mas and 4.6 degrees, respectively. This gives room for two possible scenarios: either the orbital period is considerably larger than the 8 years time difference between the observations, or it is an integer fraction of it (including ≈8 years as one possibility). The spectroscopically determined period of $P \sim 17.1$ yr is – at first sight – incompatible with this, since it would predict a difference in position angle of nearly 180 degrees for the direct imaging observations. A possible solution to this contradiction could be that HD 160934 is in fact a quadruple system (with the possible widely separated B component), and that the directly imaged companion is not identical with the spectroscopic detection. However, as pointed out in Sect. 2.5, the available RV data does not allow an unambiguous period determination. In fact, a period half the length of the suggested 17.1 years may still be compatible with the RV data and has to be confirmed or ruled out by further observations.

If we assume a period of 8.55 years, and use our mass estimates of $M_1 = 0.69$ and $M_2 = 0.57\,M_{\odot}$, then the corresponding semimajor axis would be $a = 4.5$ AU or $0\farcs12$ at a distance of 36.5 pc. Assuming an eccentricity of $e = 0.8$, this results in a maximum possible separation between the two components of $r = 8.1$ AU or $0\farcs22$, respectively. This is very close to the separation observed with AstraLux in July 2006, which then means in return that the next periastron could be expected for around mid-2008. Further RV measurements and resolved imaging in the next 2−3 years are necessary to sort out the period ambiguity and to check whether the spectroscopically and directly detected companions are indeed identical.

4. Conclusions

By combining pre-discovery HST archive data, our own high angular resolution astrometry, and unresolved photometry, we were able to derive mass and spectral type estimates for the HD 160934 system. These estimates are compatible with unresolved 2MASS photometry, Hipparcos distance measurements, and existing age estimates for HD 160934 and the AB Doradus young moving group. We suggest that the directly imaged companion may be identical with the companion discovered by radial velocity measurements, but with an orbital period of $P \approx 8.5$ years, about half the value of the published period. Further high angular resolution observations and radial velocity measurements in the next 2−3 years will allow to confirm or negate this suggestion. In the positive case, the combination of RV measurements and astrometry will instantly allow to compute a full set of orbital parameters, and to derive precise component masses. The knowledge of the orbit will enable the precise reanalysis of the Hipparcos measurements, resulting in much smaller errors for the parallax, distance, and distance module. This in return will make the HD 160934 system a valuable calibrator for pre-main-sequence stellar models.

The presented data are a good example for the power of the Lucky Imaging technique as a simple but effective tool for the discovery and follow-up of close binaries. Observations near the diffraction limit in the visible are possible with a fraction of the instrumental effort compared to adaptive optics systems or spaceborne observatories.

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References

Allard, F., Hauschildt, P., Alexander, D., & Starrfield, S. 1997, ARA&A, 35, 137
Baldwin, J. E., Tubbs, R. N., Cox, G. C., et al. 2001, A&A, 368, L1
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
Bessell, M. S., & Weis, E. W. 1987, PASP, 99, 642
Bouy, H., Brandner, W., Martín, E. L., et al. 2003, AJ, 126, 1526
Close, L. M., Lenzen, R., Guirado, J. C., et al. 2005, Nature, 433, 286
Fruchter, A. S., & Hook, R. N. 2002, PASP, 114, 144
Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748
Gálvez, M. C., Montes, D., Fernández-Figueroa, M. J., & López-Santiagio, J. 2006, Ap&SS, 304, 59
Gizis, J. E., Reid, I. N., & Hawley, S. L. 2002, AJ 123, 3356
Hartkopf, W. I., & Mason, B. D. 2006, Sixth Catalog of Orbits of Visual Binary Stars, published online at `http://ad.usno.navy.mil/wds/orb6.html`
Henry, G. W., & Fekel, F. C. 1995, AJ, 110, 2926
Hünsch, M., Schmitt, J. H. M. M., Sterzik, M. F., & Voges, W. 1999, A&AS, 135, 319
Jordi, K., Grebel, E. K., & Ammon, K. 2006, A&A, 460, 339
Krist, J., & Hook, R. 2004, The Tiny Tim User's Guide (Version 6.3), `http://www.stsci.edu/software/tinytim`
Law, N. M., Mackay, C. D., & Baldwin, J. E. 2006, A&A, 446, 739
Lopez-Santiago, J., Montes, D., Crespo-Chacon, I., & Fernandez-Figueroa, M. J. 2006, ApJ, 643, 1160
Lowrance, P. J., Becklin, E. E., Schneider, G., et al. 2005, AJ, 130, 1845
McCarthy, C., & Zuckerman, B. 2004, AJ, 127, 2871
Mulliss, C. L., & Bopp, B. W. 1994, PASP, 106, 822
Pandey, J. C., Singh, K. P., Sagar, R., & Drake, S. A. 2002, J. Astrophys. Astr., 23, 9
Perryman, M. A. C., Lindegren, L., Kovalevsky, J., et al. 1997, A&A, 323, L49
Pounds, K. A., Allan, D. J., Barber, C., et al. 1993, MNRAS, 260, 77
Reid, I. N., Hawley, S. L., & Gizis, J. E. 1995, AJ, 110, 1838
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Smith, J. A., Tucker, D. L., Kent, S., et al. 2002, AJ, 123, 2121
Tubbs, R. N., Baldwin, J. E., Mackay, C. D., & Cox, G. C. 2002, A&A, 387, L21
Weis, E. W. 1991, AJ, 101, 1882
Weis, E. W. 1993, AJ, 105, 1962
Zuckerman, B., Song, I., & Bessell, M. S. 2004, ApJ, 613, L65
Zuckerman, B., & Song, I. 2004, ARA&A, 42, 685