THE ASTRONOMICAL JOURNAL, 116:440–443, 1998 July

WIDE FIELD PLANETARY CAMERA 2 OBSERVATIONS OF PROXIMA CENTAURI: NO EVIDENCE OF THE POSSIBLE SUBSTELLAR COMPANION

DAVID A. GOLIMOWSKI[1] AND DANIEL J. SCHROEDER[2]
Received 1998 March 10; revised 1998 March 25

ABSTRACT

Two-epoch observations of Proxima Centauri using the *Hubble Space Telescope* (*HST*) Wide Field Planetary Camera 2 (WFPC2) are reported. Exposures of 10 and 40 s were recorded through the F1042M filter ($\lambda_c \approx 1$ μm), permitting examination of the circumstellar region beyond 0".09 from Proxima Cen. No evidence of a substellar companion within 0".85 of Proxima Cen is seen, which counters the recently reported detection of a faint feature by Schultz et al. using *HST*'s Faint Object Spectrograph (FOS). A feature in the WFPC2 images having a relative brightness and a separation comparable to those of the FOS feature would have been detected with a signal-to-noise ratio of ∼22. Moreover, if the FOS feature were a substellar companion, it should have appeared in our F1042M images to be about 3.7 mag fainter than Proxima Cen. Inspection of deep WFPC2 images of Proxima Cen through three filters indicates that the FOS feature is not a background object. Local enhancements of WFPC2's point-spread function suggest a possible instrumental origin for the FOS feature, but the singularity and apparent motion of the FOS feature complicate this notion.

Key words: stars: individual (Proxima Centauri) — stars: low-mass, brown dwarfs

1. INTRODUCTION

Proxima Centauri (Gliese 551, LHS 49; $V = 11.09$; spectral type M5.5 V) is the star closest to the Sun. Its proximity (1.3 pc) and low mass (0.1 $M_\odot$) have made it a popular target for seeking extrasolar planets or substellar companions. Several search techniques have been employed in this quest, including astrometry (Kamper & Wesselink 1978; Benedict et al. 1995, 1998), radial velocity (Hatzes et al. 1996), photometric variability (Benedict et al. 1993), near-infrared imagery (Jameson, Sherrington, & Giles 1983), and near-infrared speckle interferometry (Leinert et al. 1997). The results of these searches have greatly constrained the physical and dynamical characteristics of any bodies orbiting Proxima Cen. For example, Leinert et al. (1997) placed a limit of 3 to 5 *K*-band magnitudes below the empirical end of the main sequence ($M_K \approx 10$) for brown dwarf companions located 1 to 10 AU from Proxima Cen. Benedict et al. (1998) recently reported astrometric upper limits of 1 Saturn mass for companions with periods $P > 400$ days (orbital radii $r > 0.5$ AU) and 1 Jupiter mass for companions with $P = 40$ days ($r = 0.1$ AU).

Countering the trend of null results, Schultz et al. (1998, hereafter S98) reported the detection of a possible substellar companion to Proxima Cen in coronagraphic images obtained with the *Hubble Space Telescope* (*HST*) Faint Object Spectrograph (FOS). Unfiltered and reconstructed FOS images obtained 104 days apart showed two bright features—one in each image—located approximately 0".3 from Proxima Cen at position angles separated by about 65°. Although accurate flux measurements were impossible, S98 estimated that the feature is about 7 mag fainter than Proxima Cen in the effective bandpass of the FOS red detector. Unable to explain the feature as an instrumental artifact or a chance alignment with a background star, S98 suggested that the feature may be a brown dwarf in a highly eccentric, long-period orbit. They determined that such an object could have eluded astrometric detection.

We are presently engaged in a search for very low mass (VLM) companions to nearby stars using *HST*'s Wide Field Planetary Camera 2 (WFPC2) (Schroeder & Golimowski 1996). We have obtained direct images of Proxima Cen through WFPC2's F1042M filter ($\lambda_c \approx 1$ μm) at two epochs following the observations of S98. Our images reveal the circumstellar region beyond 0".09 from Proxima Cen, which includes the field of view of the FOS coronagraphic images. In this paper, we present these WFPC2 images and report no evidence of the FOS feature reported by S98. We discuss the sensitivity of our search and the likelihood of imaging the FOS feature if it were a substellar companion. Finally, we discuss the possibility that the FOS feature may be an instrumental effect, such as a local enhancement of the point-spread function (PSF).

2. OBSERVATIONS AND DATA REDUCTION

Observations of Proxima Cen were performed on UT 1997 March 30 and April 20 using WFPC2. These observations occurred within 6 months of the last FOS observation by S98. Proxima Cen was acquired at the approximate center of the Planetary Camera (PC), providing a 34" × 34" field of view (FOV) centered on the star. The telescope was rolled counterclockwise by 44° between visits to Proxima Cen, causing a like rotation of the FOV. During each visit, two 10 s exposures and five 40 s exposures were recorded at a gain of $7e^-$ DN^{-1} through the F1042M filter ($\lambda_c = 1.02$ μm, $\Delta\lambda = 0.04$ μm). Although the detective quantum efficiency of WFPC2 through F1042M is low (0.36% peak), the contrast in brightness between main-sequence stars and their putative VLM companions is smallest in this bandpass.

The images were reduced by the *HST* data calibration pipeline (Leitherer et al. 1995). Recalibration of the images with more contemporary calibration data was not necessary for the purposes described in this paper. The images of each exposure set were combined using a pixel rejection

[1] Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218.
[2] Department of Physics and Astronomy, Beloit College, 700 College Street, Beloit, WI 53511.

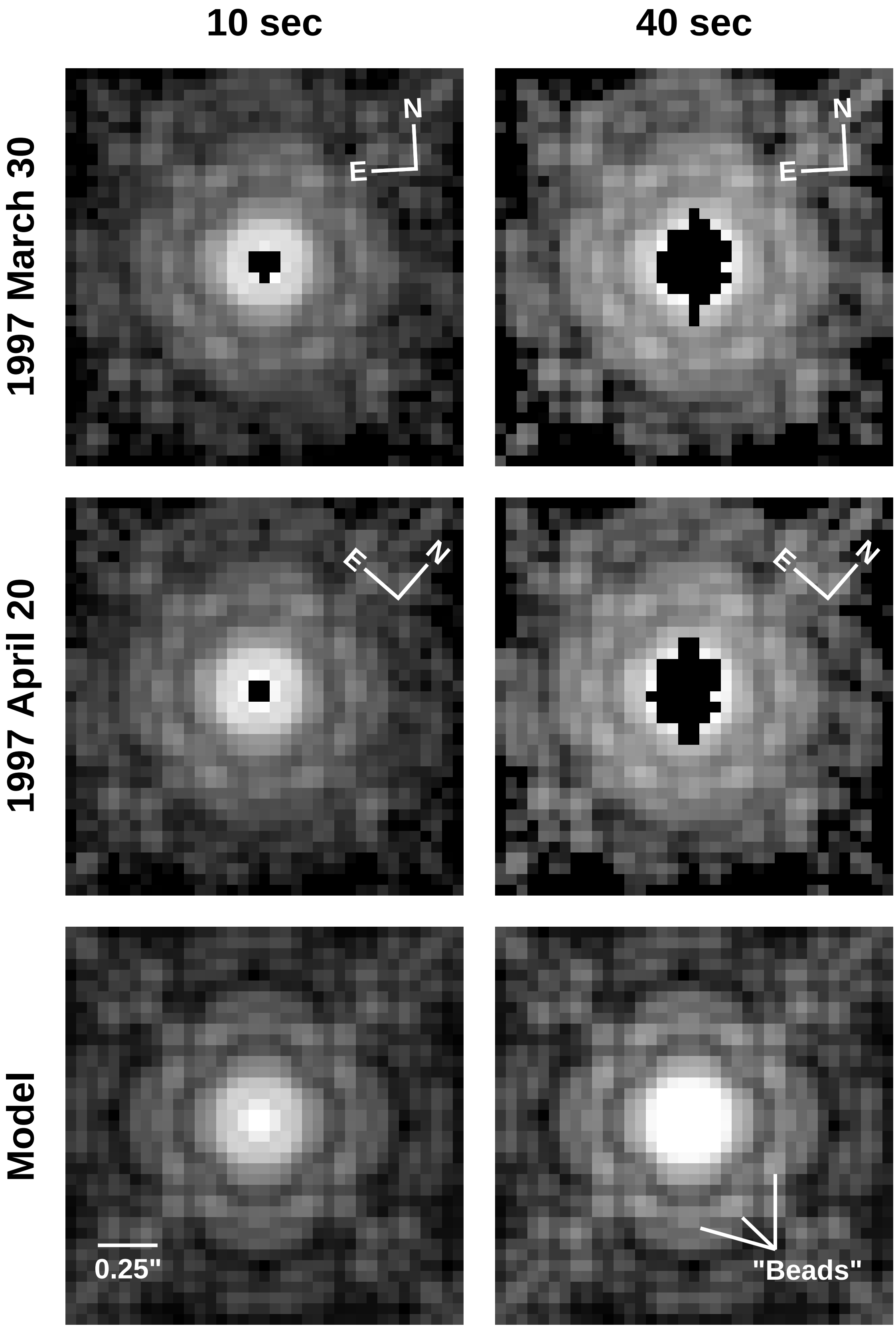

FIG. 1.—PC images of Proxima Cen through the F1042M filter. The top and middle panels show the 10 and 40 s exposures obtained on UT 1997 March 30 and April 20, respectively. The logarithms of the pixel intensities are displayed to reduce image contrast. The saturated pixels near the image centers have been blackened to demark the observable circumstellar region. The bottom panels show model images of the PC's PSF through F1042M. These panels display the same model suitably scaled to mimic the level of exposure of the actual PC images above. Each panel depicts a $1''.7 \times 1''.7$ section of the full PC image centered on the star. This FOV is the same observed by S98 using the large barred aperture of FOS. No evidence of the FOS companion candidate is seen. The beadlike features on the bright fourth Airy ring lie $\sim 0''.4$ from the image center and are ~ 6.5 mag fainter than the image core.

algorithm that eliminates artifacts, such as cosmic rays, that deviate by at least 3 σ from the local mean.

3. RESULTS

Figure 1 shows the 10 and 40 s images of Proxima Cen obtained on UT 1997 March 30 (*top*) and UT 1997 April 20 (*middle*). The logarithms of the pixel intensities are displayed to reduce image contrast. Each panel depicts a 1″.7 × 1″.7 section of the full PC image centered on the star. Thus, the panels show the same FOV around Proxima Cen observed by S98 using the large barred aperture of FOS. The saturated pixels near the center of each image have been blackened to demark the observable circumstellar region. Using an image scale of 0″.04554 pixel^{-1} for the PC (Holtzman et al. 1995), we compute the radial extent of saturated pixels to be 0″.09 and 0″.20 for the 10 and 40 s exposures, respectively. By comparison, the half-width of the FOS occulting bar used by S98 was 0″.15.

Because the images of Proxima Cen are saturated, conventional aperture photometry cannot be used to measure the star's flux through F1042M. An estimate of this flux can be made, however, by comparing the unsaturated region of the PSF with that of another well-exposed but unsaturated star. Golimowski et al. (1998) obtained unsaturated F1042M images of the M1 V star Gliese 229A. By suitably scaling the azimuthally averaged PSF of Proxima Cen to match that of Gl 229A, we estimate a WFPC2 magnitude of $m_{1042} \approx 6.0$ for Proxima Cen.

The bottom panels of Figure 1 show model images of the PC's PSF through the F1042M filter. Each panel displays the same model image suitably scaled to mimic the level of exposure of the actual PC images in the same column of panels. The models were generated in the manner described by Schroeder & Golimowski (1996) for a star centered on the contiguous corners of four pixels. The PSFs have been convolved with a 9 × 9 pixel kernel that simulates the pixel response function of the WFPC2 detectors (Burrows et al. 1995). Aberrations caused by mirror-polishing errors are not included in the models, but their effect on the PSF is not large for bandpasses as red as F1042M (Krist & Burrows 1995).

The good match between the images of Proxima Cen and our single-PSF models indicates that only one stellar source has been imaged in the FOV. Each pointlike feature in the PC images has a counterpart in the model PSF. (Subtle differences between the actual and model PSFs are attributable to subpixel offsets of the image centers. Note that the images obtained on UT 1997 April 20 are nearly centered, like the models, on the contiguous corners of four pixels.) None of the pointlike features move as the FOV rotates between visits, so these features cannot be images of astronomical sources.

Of the many features present in the PC's complex PSF, one deserves special mention. The bright annulus of radius ~0″.4 (9 pixels), visible in both the real and model images, is the enhanced fourth Airy ring that is characteristic of a circular aperture with a central obscuration ratio of 0.41 (Schroeder 1987, p. 182). This diffraction effect is illustrated in Figure 2. The surface brightness of the fourth ring is modulated by diffraction from the primary- and secondary-mirror support structures, which produces compact "beads" that are approximately 6.5 mag fainter than the core of the PSF. These "beads" are useful benchmarks for determining the sensitivity of our images to substellar companions.

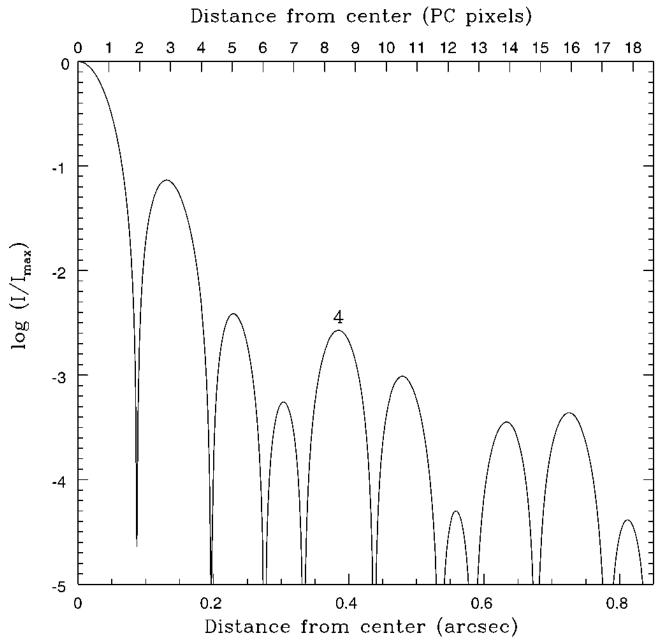

FIG. 2.—Radial plot of the theoretical Airy diffraction pattern for a circular aperture with central obscuration ratio of $\epsilon = 0.41$ and a monochromatic wavelength of 1.02 μm. Binning this pattern to the pixel resolution of the PC produces a PSF similar to that shown in Fig. 1. Note the prominence of the fourth diffraction ring (marked "4") at a distance of ~0″.4 (9 pixels). Modulation of this ring's intensity by *HST*'s mirror-support structures causes the beading effect seen in Fig. 1. Similar "beads" are present in the FOS PSF at locations governed by $\epsilon = 0.33$ and the effective wavelength of the FOS image.

Our PC images of Proxima Cen recorded 21 days apart exhibit no evidence of the possible companion noted by S98 from their coronagraphic FOS images. The 10 σ threshold for detecting point sources located 0″.3 from Proxima Cen (the average separation of the FOS feature) is $M_{1042} \approx 17.6$ for the 40 s images. This threshold is 1.3 absolute magnitudes fainter than the brown dwarf Gl 229B in this bandpass (Golimowski et al. 1998). A feature in these images having a relative brightness and a separation comparable to those of the FOS feature would have been detected with a signal-to-noise ratio of ~22.

4. DISCUSSION

Using count rates derived from model brown dwarf spectra, S98 concluded that the FOS feature, if real, is consistent with a brown dwarf that is about 6 times more luminous than Gl 229B (Nakajima et al. 1995) in the effective bandpass of the unfiltered FOS red detector. To investigate this claim and its implications, we have listed in Table 1 the measured optical and near-infrared magnitudes of several known late-type objects. Although the magnitudes listed in Table 1 come from different photometric systems, the colors of such red objects in these systems are similar.

Using the measured FOS count rate from the M6 V star Wolf 359, S98 estimated a Gunn magnitude of $r \approx 15.8 \pm 0.5$ for the FOS feature. Assuming the feature shares Proxima Cen's parallax of 0″.77233 (ESA 1997), we compute $M_r \approx 20.2 \pm 0.5$. Thus, the feature is about 17 times less luminous than the M9 V star LHS 2065 (Bessell 1991) and about 60 times more luminous than the brown dwarf Gl 229B (Golimowski et al. 1998) at R-band wave-

TABLE 1

OPTICAL AND NEAR-INFRARED PHOTOMETRY OF VERY LOW MASS OBJECTS

Object	Spectral Type	V, M_V	R, M_R	I, M_I	m_{1042}, M_{1042}	J, M_J
Gl 229A	M1 V	8.12,[a] 9.31[b]	7.16,[a] 8.35[b]	6.11,[a] 7.30[b]	5.48,[e] 6.67[b]	4.98,[a] 6.17[b]
Proxima Cen......	M5.5 V	11.09,[a] 15.53[b]	9.44,[a] 13.88[b]	7.44,[a] 11.88[b]	6.0,[f] 10.4[b]	5.28,[a] 9.72[b]
Gl 644C	M7 V	16.80,[a] 17.75[c]	14.65,[a] 15.60[c]	12.24,[a] 13.19[c]	...	9.77,[a] 10.72[c]
LHS 2065	M9 V	18.74,[d] 19.08[c]	16.74,[d] 17.09[c]	14.54,[d] 14.89[c]	...	11.30,[d] 11.65[c]
Gl 229B	Brown dwarf	...	23.41,[e] 24.60[b]	19.57,[e] 20.76[b]	15.18,[e] 16.37[b]	14.2,[g] 15.4[b]

[a] Photometry from Leggett 1992.
[b] Parallax from ESA 1997.
[c] Parallax from van Altena, Lee, & Hoffleit 1995.
[d] Photometry from Bessell 1991.
[e] Photometry from Golimowski et al. 1998.
[f] Photometry from this paper.
[g] Photometry from Matthews et al. 1996.

lengths. This result is a necessary condition for a substellar classification of the FOS feature, but it is not a sufficient one, as we now show.

Because Gl 229B is the only VLM object so far measured through F1042M, it is impossible to predict accurately the brightness of the FOS feature in this bandpass. However, we may estimate this quantity by interpolating bilinearly between the magnitudes listed in Table 1 for Proxima Cen, LHS 2065, and Gl 229B. Doing so, we obtain $m_{1042} \approx 9.7$. Thus, the FOS feature should have appeared in our F1042M images to be ~ 3.7 mag fainter than Proxima Cen and ~ 3.2 mag brighter than the "beads" on the fourth Airy ring. No such feature is seen in the PC images recorded during either visit. Therefore, we conclude that the FOS feature cannot be a VLM or brown dwarf companion to Proxima Cen.

If the FOS feature is not a substellar companion, then what is it? The sensitivity limit described at the end of § 3 discourages the notion that the feature shines by neutral scattering of starlight from Proxima Cen. Moreover, deep (400 s) F1042M exposures of Proxima Cen recorded during both WFPC2 visits show no background objects at the projected locations of the FOS aperture during S98's observations of Proxima Cen. Earlier *R*- and *I*-band PC images of Proxima Cen from our program also reveal no field sources in the corresponding locations of the FOS aperture (S98). Thus, we are unable to provide a viable interpretation of the FOS feature as an image of a known type of astronomical object.

Because FOS was rarely used for scientific imaging, its PSF was formally characterized only once (Koratkar 1996). Then, the white-light PSF of the red detector exhibited a linear feature that was oriented nearly perpendicularly to the occulting bar. This linear feature was attributed to "diffraction spikes convolved with the COSTAR [Corrective Optics Space Telescope Axial Replacement] mirrors in the PSF." Unfortunately, the positional or temporal behavior of the FOS PSF was never studied (E. Smith 1998, personal communication), so the possibility that S98's feature is an artifact of a variable PSF cannot be rigorously assessed. S98 discounted the possibility of an instrumental artifact because they observed no similar features near the other target stars in their survey. However, those stars (Wolf 359, LHS 292, Gl 293, GJ 1245AC, and Wolf 424AB) are 1.5–4.5 mag fainter than Proxima Cen (Leggett 1992), so compact features of their PSFs—like the "beads" described in § 3—would probably have been fainter than S98's detection threshold of $V \approx 20$.

Given the lack of corroborating evidence in our PC images and the understudied nature of the FOS PSF, we do not support S98's proposition that the FOS feature is a substellar companion to Proxima Cen. Although we cannot definitively describe the nature of the FOS feature, neither can we explain it as an astronomical phenomenon. Local enhancements of the PC's PSF suggest a possible instrumental origin for the FOS feature, but the singularity and apparent motion of the FOS feature complicate this notion. Certainly, additional observations will help to settle this issue.

The authors thank Peg Stanley for her assistance in implementing the observations. We also thank Ed Smith for a helpful discussion of the FOS PSF. Support for this work was provided by NASA grants NAG 5-1617 and NAG 5-1620. The Space Telescope Science Institute is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

REFERENCES

Benedict, G. F., et al. 1998, BAAS, 29, 1316
———. 1995, Ap&SS, 223, 137
———. 1993, PASP, 105, 487
Bessell, M. S. 1991, AJ, 101, 662
Burrows, C. J., et al. 1995, Wide Field and Planetary Camera 2 Instrument Handbook (version 3.0; Baltimore: STScI)
ESA. 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200) (Noordwijk: ESA)
Golimowski, D. A., Burrows, C. J., Kulkarni, S. R., Oppenheimer, B. R., & Brukardt, R. A. 1998, AJ, in press
Hatzes, A. P., Kürster, M., Cochran, W. D., Dennerl, K., & Döbereiner, S. 1996, J. Geophys. Res., 101, 9285
Holtzman, J., et al. 1995, PASP, 107, 156
Jameson, R. F., Sherrington, M. R., & Giles, A. B. 1983, MNRAS, 205, 39P
Kamper, K. W., & Wesselink, A. J. 1978, AJ, 83, 1653
Koratkar, A. 1996, Pre-COSTAR and Post-COSTAR Observed Point Spread Functions for the FOS (Instrum. Sci. Rep. CAL/FOS-148) (withdrawn pending rev.; Baltimore: STScI)
Krist, J. E., & Burrows, C. J. 1995, Appl. Opt., 34, 4951
Leggett, S. K. 1992, ApJS, 82, 351
Leinert, C., Henry, T., Glindemann, A., & McCarthy, D. W. 1997, A&A, 325, 159
Leitherer, C., ed. 1995, *HST* Data Handbook (version 2.0; Baltimore: STScI)
Matthews, K., Nakajima, T., Kulkarni, S. R., & Oppenheimer, B. R. 1996, AJ, 112, 1678
Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., & Durrance, S. T. 1995, Nature, 378, 463
Schroeder, D. J. 1987, Astronomical Optics (San Diego: Academic)
Schroeder, D. J., & Golimowski, D. A. 1996, PASP, 108, 510
Schultz, A. B., et al. 1998, AJ, 115, 345 (S98)
van Altena, W. F., Lee, J. T., & Hoffleit, E. D. 1995, The General Catalogue of Trigonometric Stellar Parallaxes (4th ed.; New Haven: Yale Univ. Obs.)