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MID-INFRARED IMAGING OF THE POST–ASYMPTOTIC GIANT BRANCH STAR AC HERCULIS WITH THE MULTIPLE MIRROR TELESCOPE ADAPTIVE OPTICS SYSTEM[1]

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ABSTRACT

We utilized the unique 6.5 m Multiplie Mirror Telescope deformable secondary adaptive optics (AO) system to produce high-resolution (FWHM = 0″.3), very high Strehl mid-infrared (9.8, 11.7, and 18 μm) images of the post–asymptotic giant branch star AC Her. The very high (98% ± 2%) Strehls achieved with mid-IR AO led naturally to an ultrastable point-spread function (PSF) independent of air mass, seeing, or location on the sky. We find no significant difference between AC Her's morphology and our unresolved PSF calibration stars (μ UMa and α Her) at 9.8, 11.7, and 18 μm. Our current observations do not confirm any extended mid-IR structure around AC Her. These observations are in conflict with previously reported Keck (seeing-limited) 11.7 and 18 μm images that suggested the presence of a resolved ∼0″.6 edge-on circumbinary disk. We conclude that AC Her has no extended mid-IR structure on scales greater than 0″.2 ($R < 75$ AU). These first results of mid-IR AO science are very encouraging for future high-accuracy mid-IR imaging with this technique.

Subject headings: binaries: general — instrumentation: adaptive optics — stars: AGB and post-AGB — stars: evolution — stars: formation

On-line material: color figure

1. INTRODUCTION

Recent evidence suggests that at least a few post–main-sequence giants have acquired long-lived orbiting disks of dust and molecular gas (Jura & Kahane 1999). It has been suggested that these dust disks around post–main-sequence stars may possibly lead to planet formation (Jura, Chen, & Werner 2000). It would be quite revolutionary if the process of planet formation occurs at both the "pre–" and "post"–main-sequence phases of a star's lifetime. Since post–main-sequence stars are much more luminous ($L \sim 1000$–$10{,}000\ L_\odot$) than pre–main-sequence stars and have stronger winds and outflows, there should be very interesting interactions between the disks and these outflows. Ultimately one might be able to learn more about the disk/planet formation process if these asymptotic giant branch (AGB) disks can be confirmed. Here we report observations of one of the most interesting of these post-AGB circumstellar disks: AC Her.

The post-AGB spectroscopic binary star AC Her may be the prototype of these AGB disk systems. AC Her is one of the most luminous ($L \sim 1000\ L_\odot$) and closest ($D \sim 750$ pc; Shenton et al. 1992) pulsational variables transiting from the AGB to the planetary nebula phase (an RV Tauri star). AC Her is a luminous mid-IR source ($F_\nu = 42$ Jy at 12 μm from *IRAS*) indicating significant circumstellar dust. Shenton et al. (1992) find that AC Her's optical and IR light curves can be explained by circumstellar dust around a nonradial pulsator. The origin and nature of this circumstellar dust have been the subject of speculation. Jura & Kahane (1999) argue that the very narrow (FWHM ∼ 5 km s^{-1}) CO (2–1) emission line (Bujarrabal et al. 1988) in AC Her is a signature of a gravitationally bound (not outflowing) long-lived reservoir of orbiting gas and dust. Van Winckel et al. (1998) also argue that there is strong evidence that such a reservoir of dust may be long-lived and disklike. Jura & Kahane (1999) further argue that grains in size from 0.2 to 20 μm are present and that grain growth to planetesimal formation is possible. Encouraged by the submillimeter CO observations of Bujarrabal et al. (1988), Jura et al. (2000) obtained 11.7 and 18.7 μm images of AC Her at the 10 m Keck telescope in 1999 May and August. The resulting Keck point-spread function (PSF) FWHM ∼ 0″.35–0″.45 (11.7 and 18.7 μm) images were the sharpest ever taken of AC Her.

The Keck images of Jura et al. (2000) suggest that AC Her is clearly resolved at 18.7 μm into north and south unresolved "points" separated by ∼0″.6 (see our inset in the upper right of Fig. 1). Jura et al. (2000) modeled this image as an edge-on ring of dust of radius 300 AU in orbit around the 1.39 AU binary AC Her. They speculated that a binary such as AC Her could produce a small circumbinary ring of dust that would expand to a radius of 300 AU over time. They argued that this dust ring would be primarily composed of long-lived ∼200 μm particles that could collide to create the IR-emitting 1 μm grains observed in the mid-IR images. However, since their model relies on the morphology of the mid-IR images, it is important to confirm this morphology at higher Strehls. Hence, we present here very high Strehl mid-IR images of AC Her obtained with adaptive optics (AO).

2. OBSERVATIONS

We have utilized the University of Arizona adaptive secondary AO system to obtain high-resolution images of AC Her and several PSF calibration stars. The 6.5 m MMT telescope has a unique AO system. To reduce the aberrations caused by atmospheric turbulence, all AO systems have a deformable mirror (DM) that is updated in shape at ∼500 Hz (Close 2000, 2003). Until now, all AO systems have located this DM at a reimaged pupil (effectively a compressed image of the primary mirror). To reimage the pupil onto a DM typically requires six to eight additional warm optical surfaces, and this significantly increases the thermal background and decreases the optical

[1] The results presented here made use of the of Multiple Mirror Telescope (MMT) Observatory, a facility jointly operated by the University of Arizona and the Smithsonian Institution.

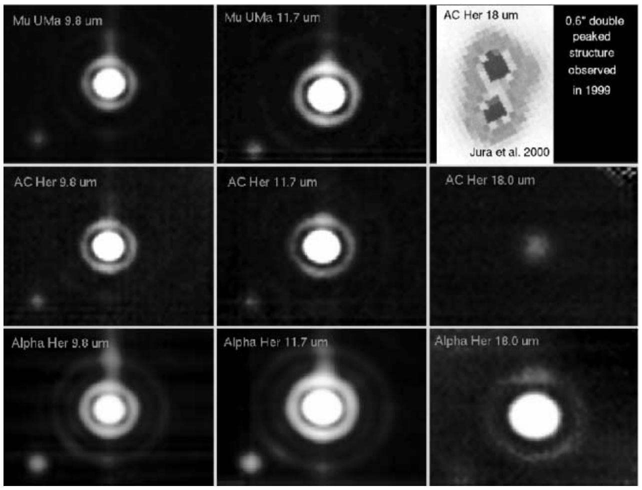

FIG. 1.—The 9.8, 11.7, and 18 μm images of AC Her and PSF stars μ UMa and α Her as observed at the MMT. In the upper right-hand corner, we have inserted the published 18 μm Keck image of AC Her (in false color; Jura et al. 2000). The box size of the MMT images is 1″.5 × 1″.0; the effective scale of the Keck image is similar with a box size of ~0″.7 × 1″.0. Note how there is no sign of any extended structure in the MMT AC Her images in any of the filters. The faint point source in the lower left of each MMT image is a MIRAC3 ghost. [*See the electronic edition of the Journal for a color version of this figure.*]

throughput of the system (Lloyd-Hart 2000; Lloyd-Hart et al. 2003). The MMT utilizes a completely new type of DM, which serves as both the secondary mirror of the telescope and the DM of the AO system. In this design, there are no additional optics required in front of the science camera, the emissivity is lower, and thermal IR AO imaging becomes feasible.

The DM consists of 336 voice coil actuators that drive 336 small magnets glued to the back surface of a thin (2.0 mm thick) 642 mm aspheric ULE glass "shell" (for a detailed review of the secondary mirror, see Brusa et al. 2003). Complete positional control of the surface of this reflective shell is achieved by use of a capacitive sensor feedback loop. This positional feedback loop allows one to position an actuator of the shell to within 4 nm rms (total surface errors amount to only 40 nm rms over the whole secondary). The AO system samples at 550 Hz using 108 active subapertures. For a detailed review of the MMT AO system, see Wildi et al. (2003) and references therein.

2.1. *MMT Mid-IR AO Observations*

We observed AC Her on the night of 2003 May 13 (UT). The AO system corrected the lowest 52 system modes and was updated at 550 Hz guiding on AC Her itself ($V = 7.03$ mag). The closed-loop -3 dB bandwidth was estimated at 30 Hz. At 1.65 μm (*H* band), this level of correction leads to Strehls of ~0.20 (Close et al. 2003). Since the size of a coherent patch of air (r_0) increases with $\lambda^{6/5}$, imaging without AO correction can obtain images close to diffraction-limited in FWHM once $\lambda > 8$ μm. However, such "seeing-limited" non-AO mid-IR images only approach Strehls of ~0.5, which can lead to significant instability in the PSF calibration (since approximately half the light is outside the telescope's diffraction pattern PSF). Our AO correction vastly improved our AC Her images to nearly perfect Strehls (~0.98 ± 0.02).

2.1.1. *The Mid-Infrared Array Camera*

We utilized the 128 × 128 SiAs blocked-impurity-band 2–20 μm Mid-InfraRed Array Camera (MIRAC3; Hoffmann et al. 1998). The 0″.088 pixel^{-1} scale was used with the 9.8, 11.7, and 18 μm 10% bandwidth filters. To remove thermal and detector instabilities, we chopped at 1 Hz with an internal cold chopper in the interface Dewar BLINC (BracewelL Infrared Nulling Cryostat; Hinz et al. 2000) between the AO system and MIRAC3.

We observed with the AO system locked continuously on AC Her. The 15° tilted BLINC Dewar window is a high-quality dichroic that reflected the visible light ($\lambda < 1$ μm) to the AO wave-front sensor and transmitted the IR through BLINC to MIRAC3. Since the internal chopper in BLINC was past the dichroic, continuous 1 Hz chopping did not affect the visible light beam, and hence the AO lock was unaffected. To further calibrate the background (in addition to chopping), we nodded ~6″–8″ in the telescope's azimuth direction (the horizontal direction in Fig. 1) every minute. The internal chopper was set to run in the altitude direction (the vertical direction) with a chop throw of ~20″. The derotator was disabled during these observations to help minimize the residual background structure as well. The 0″.505 Washington Double Star Catalog astrometric binary WDS 02589+2137BU was observed earlier (2003 November 25 UT, with a position angle of 269°) and was used to calibrate the camera's orientation and its 0″.088 pixel^{-1} plate scale.

2.1.2. *Reducing the Mid-IR AO Images*

For the 9.8, 11.7, and 18 μm filters, we obtained 8 × 1 minute co-added chop differenced images (one image from each nod). Four of these were beam A nods interlaced with four beam B nods. We utilized a custom IRAF script to reduce this mid-IR data (Biller et al. 2003). The script produced eight background-subtracted images by subtracting nod B from the following nod A (and the A nods from the B nods). The resulting eight images were bad pixel–corrected and flat-fielded. The pipeline cross-correlates and aligns each individual nod image (to an accuracy of ~0.02 pixels), then rotates each image (by 270° minus the current parallactic angle) so that north is up and east is to the left. However, there was ≤10° net parallactic rotation for any one filter observation (over a period of ~8 minutes); hence, nonrotated images were also processed on a parallel track. These final aligned images were median-combined. Figure 1 illustrates the final AC Her images (nonrotated version).

The mid-IR images of the PSF calibration stars (μ UMa and α Her; observed before and after AC Her, respectively) were obtained and reduced in an identical manner to AC Her. In Figure 1, we illustrate our reduced PSF and AC Her images.

2.2. *The PSF Star μ UMa*

The star μ UMa is a well-known spectroscopic binary (SB) with a period of 230.089 days and a small eccentricity ($\epsilon = 0.06$; Batten, Fletcher, & MacCarthy 1989). At an *Hipparcos* distance of 76.3 pc, this suggests an average separation of ~1.2 AU. Hence, this binary would only subtend a maximum angle of 0″.02 on the sky. Since this is a factor of 10 less than our resolution limit, the SB μ UMa should not appear different in any significant way from a point source with a 6.3 m telescope in the mid-IR. Hence, μ UMa is a perfectly reasonable PSF star for this Letter. Moreover, there are no reports of extended mid-IR structures resolved around μ UMa to date.

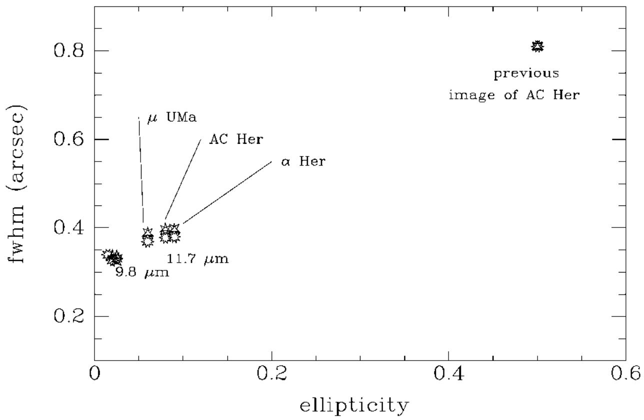

FIG. 2.—The 9.8 and 11.7 μm FWHMs and ellipticities of AC Her and the PSF stars μ UMa and α Her (the Gaussian fit FWHMs are the upper star symbols, and the enclosed FWHMs are represented by the slightly lower star symbols; AC Her is the middle data set in the 9.8 and 11.7 μm clusters). The location of the "double-peaked" morphology is estimated from the previous Keck image (FWHM ~ 0$''$.8; Jura et al. 2000) shown in the upper right. Note that AC Her's morphology appears much more consistent with that of the PSF stars at 9.8 and 11.7 μm than an extended FWHM ~ 0$''$.8 disk.

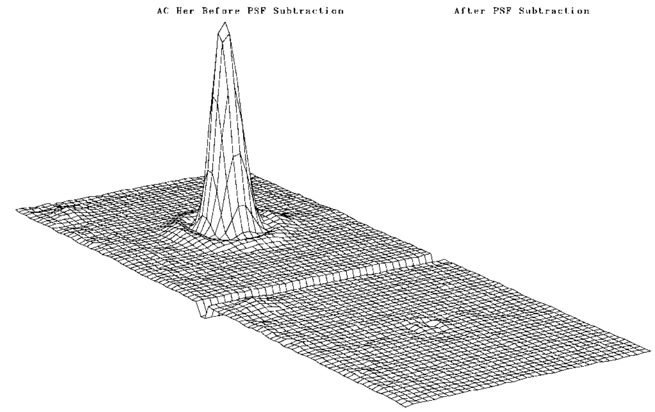

FIG. 3.—The 11.7 μm PSF of AC Her before (*left*) and after (*right*) PSF subtraction (using α Her as the PSF) with DAOPHOT's ALLSTAR task. The residual flux after PSF subtraction is less than 0.5% of AC Her's original flux. Similar residuals resulted from PSF subtractions at 9.8 and 18 μm. Based on these excellent subtractions, it appears that AC Her is not detectably extended. Note that the small ghost image to the lower left in each frame is not subtracted in order to show that the vertical scales are the same for both images.

2.3. *The PSF Star α Her*

We also utilized α Her as a PSF star. This star is part of a wide binary system with a fainter (SB) companion located ~4$''$.84 (567 AU) away (Fabricius et al. 2002). This companion is not mid-IR luminous and was not in our field of view; hence, it did not affect our PSF image of the α Her primary. However, in 1993, the α Her primary was observed by the Infrared Spatial Interferometer (ISI; Danchi et al. 1994) to have a 0$''$.25–0$''$.35 thin shell in the mid-IR. We do not detect any evidence of such a shell around the α Her primary in our mid-IR AO observations. This is not surprising given that more recent 1999–2001 ISI measurements also fail to detect any shell around α Her (S. Tevosian 2003, private communication). Hence, as noted by Weiner, Hale, & Townes (2003), this shell may have evolved since the 1993 ISI measurements of Danchi et al. (1994). It is not clear how an R ~ 0$''$.25–0$''$.35 (29–41 AU) shell could become undetectable to the ISI in a period of ~6 years. A detailed discussion of the current lack of extended structure in the recent ISI interferometric measurements is beyond the scope of this Letter. For now, we simply note that α Her appears to be currently unresolved (on scales >0$''$.2), and hence we will utilize it as a PSF star in this Letter.

3. REDUCTIONS

We found that the AC Her data appeared consistent with an unresolved point source. We measured the FWHM, ellipticity, and positional angle of any such ellipticity for all the images in Figure 1. In Figure 2, we plot the ellipticity and FWHM for our data set. As is clear from Figure 2, our AC Her data are very consistent with the PSF stars. Moreover, DAOPHOT's PSF fitting routine ALLSTAR (Stetson 1987) found AC Her to be highly consistent (to within 0.5%; see Fig. 3) with an unresolved point source (α Her). Hence, it appears that AC Her is pointlike in our data.

We also deconvolved AC Her by both the PSF stars μ UMa and α Her. Due to the very high Strehl (~0.98) and high signal-to-noise ratio in our PSF images, we could detect low-contrast structure on scales of ~0$''$.2 with the IRAF Lucy deconvolution task (Biller et al. 2003). Even at these small spatial scales, we detected no significant extended structure in the deconvolved images.

4. ANALYSIS

As is clear from Figures 1–3, AC Her is a point source and is incompatible with the resolved (0$''$.6 double-peaked) morphology previously observed at Keck and reported by Jura et al. (2000). We have confirmed that we indeed observed AC Her, since the telescope coordinates were checked twice by an offset from a nearby SAO star. The measured 11.7 μm flux of our object (~35 Jy) was in agreement with that of AC Her measured by *IRAS* (42 Jy at 12 μm). The possibility of locking the AO system on another $V = 7$ mag object with ~35 Jy at 11.7 μm at the location of AC Her (R.A. $= 18^h30^m16^s.2$, decl. $= +21°52'01''$ [J2000])—where there are no other nearby 10 μm sources—is highly unlikely.

Hence, concluding that we did indeed observe AC Her, it appears impossible to explain how a long-lived, R ~ 300 AU circumbinary disk could have disappeared since the 1999 observations of Jura et al. (2000). Our deep images (3 σ ~ 0.1 Jy) at 9.8 and 11.7 μm would have easily detected the 0$''$.6 "double-peaked" structure reported by Jura et al. (2000). The BLINC dichroic and pupil lens unfortunately stops transmitting longward of ~18 μm; consequently, our 18 μm images have a low throughput and are weighed toward the blue end of the 10% filter. However, we would have easily detected the double peak, even in our low signal-to-noise ratio 18 μm image, but there is no sign of any 0$''$.6 double-peaked structure at 18 μm either.

AC Her's lack of any extended structure subtending an FWHM angle (θ_{disk}) greater than 0$''$.2 allows one to place lower limits on the temperature of dust, providing the 41 Jy of flux observed by *IRAS* at 12 μm. The low line-of-sight optical extinction [$E(B-V) = 0.17$ mag] to the star and the narrow CO line width observations of Bujarrabal et al. (1988) strongly suggest that the IR flux is produced by a nearly face-on disk. Our images imply an upper limit to the disk diameter of 0$''$.2 ($D_{disk} \lesssim 150$ AU), which, for optically thick emission, implies a minimum average brightness temperature over the disk of

≥200 K to produce the 12 μm *IRAS* flux of 41 Jy. Simple blackbody emission is clearly inconsistent with the observed spectral energy distribution (SED). Our result for the apparent upper limit to the diameter of the disk at 12 μm poses a severe challenge to a satisfactory dust disk model. In particular, this size limit is incompatible with the dust model of Shenton et al (1992), who proposed dust shells of 0″.5 and 0″.9 diameter. Moreover, the *Infrared Space Observatory* observations of sharp features in the mid-IR spectrum of AC Her as well as the time variability (Shenton et al. 1992) require that a significant population of small warm grains exists, while the far-IR/millimeter spectral index is essentially the Rayleigh-Jeans formula, implying emission from large cold grains (Jura et al. 2000). A possible model consistent with our upper limit on the size is a flared disk of large particles with a surrounding "halo" of small particles, as suggested by Jura et al. (2000), but either truncated or of such low surface brightness at 12 μm as to be undetected in our images beyond a diameter of 0″.2. A flared disk model, such as proposed by Jura (2003) for HD 233517, might offer an explanation for the SED as well as the time-variable IR flux and spectral features. The interior of the disk will be a long-lived reservoir of large grains, which is surrounded by a halo of small grains. A detailed model calculation for the radiative transfer is required but is beyond the scope of this Letter.

5. CONCLUSIONS

We find no morphological evidence of any resolved structure around AC Her. The combination of adaptive optics with a deformable secondary allows very high Strehl images and high PSF stability regardless of the seeing, air mass, or target brightness. We are confident that AC Her appears unresolved in the mid-IR on scales of ≥0″.2. This conclusion may impact current theories about whether or not (or how) AGB binaries can produce large ($R \sim 300$ AU) long-lived circumbinary disks since AC Her was the prototypical object. The hypothesis of a large $R \sim 300$ AU circumbinary ring around AC Her seems unlikely in light of these observations; however, a smaller $R_{\rm disk} < 75$ AU ($D \sim 750$ pc) circumbinary disk cannot be ruled out.

Adaptive optics at mid-IR wavelengths appears to be a very promising new technique that allows for uniquely stable PSFs and high Strehls. A high degree of PSF stability will eliminate morphological ambiguities due to poor (seeing-limited) PSF calibrations. Mid-IR AO should have a significant impact on any field where mid-IR imaging is possible.

These MMT observations were made possible with the hard work of the entire Center for Astronomical Adaptive Optics (CAAO) staff at the University of Arizona. In particular, we would like to thank Tom McMahon, Kim Chapman, Doris Tucker, and Sherry Weber for their endless support of this project. The wide-field AO CCD was installed by graduate student Nick Siegler. Dylan Curly helped develop the MMT AO system user interface. Graduate student Wilson Liu helped run the MIRAC3 during the run. The adaptive secondary mirror is a joint project of University of Arizona and the Italian National Institute of Astrophysics–Arcetri Observatory. We would also like thank the whole MMT staff for their excellent support and flexibility during our commissioning run at the telescope.

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