The Adaptive Optics Point Spread Function from Keck and Gemini

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ABSTRACT

From analyzing adaptive optics (AO) images of stars obtained at Keck (10 m telescope) and Gemini North (8 m telescope) Observatories, we verify that in general, the AO point spread function (PSF) can be modeled as a Lorentzian or a Lorentzian plus an Airy. However, an additional Gaussian component in the Gemini PSF is associated with an observed degraded AO performance.

1. BACKGROUND

As part of a long term effort to study asteroids with adaptive optics (AO) on the world's largest telescopes [1 2 3], we have accumulated many observations of stars to serve as checks of the point spread function (PSF). We have previously determined [4 5] that for our purposes of deriving asteroid shapes and sizes, the AO PSF can be modeled at low to moderate Strehls as a Lorentzian

$$L = I_0/[1 + (r/h)^2] \quad , \qquad 1$$

where I_0 is the peak amplitude and h is the HWHM (which can be elliptical). At higher Strehls, the AO PSF becomes the sum of a Lorentzian and an Airy,

$$A = I_0 2J_1(\pi r/2r_A)/(\pi r/2r_A) \quad , \qquad 2$$

where J_1 is the Bessel function of the first kind of order 1, and r_A is the Airy radius, or $\lambda/2D$, half the diffraction limit. The Airy then represents the AO-corrected diffraction pattern of a telescope and the Lorentzian represents the under-corrected portion of the AO PSF. Therefore, when we simultaneously fit for the asteroid and PSF in the Fourier domain, it is not necessary to make reference to an actual observation of a star; it is sufficient to fit for the appropriate PSF analytical function. However, it is instructive to more closely examine the images of these check stars by fitting them with combinations of functions in order to assess AO performance.

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2. KECK-II

From two runs with AO on the Keck Observatory's 10 m, we fit all of the observed stars with a Lorentz plus Airy. Figure 1 shows the radii of the Lorentz and Airy from these two-component fits on both nights. The top plot in Fig 1 shows the HWHM of the Airy pattern and the Lorentz semi-major and -minor axes for 90 images of 18 stars on August 16, 2006 [3], when the wavelength of the observations was $\lambda = 2.146\ \mu$m with a filter width of $\Delta\lambda = 0.311\ \mu$m. Disregarding the last 10 observations, the mean Strehl was 0.57 ± 0.04 on this night. The bottom plot in Fig 1 shows the same for 75 images of 5 stars obtained on June 7, 2009, at $\lambda = 2.124\ \mu$m and $\Delta\lambda = 0.350\ \mu$m. Disregarding the first and last 15 observations, the mean Strehl was 0.50 ± 0.03 on this night. Despite the scatter of the Lorentz sizes, and with short stretches of exceptions, the Airy sizes on both occasions reflect the expected diffraction radius. Overall, the Lorentz plus Airy is a good model for the Keck AO system.

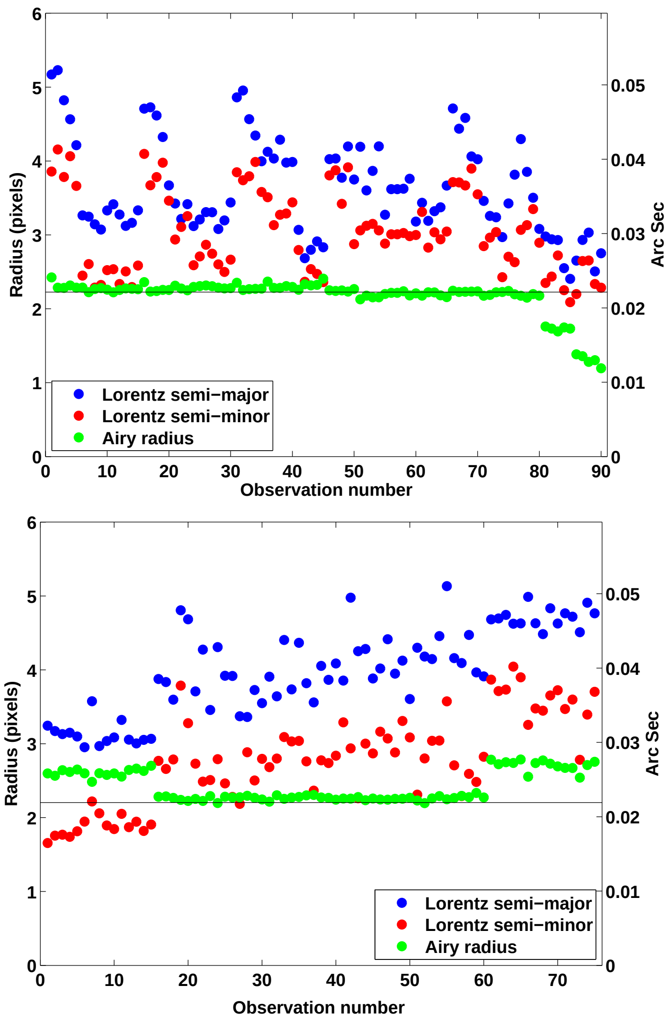

Figure 1. 2006 (top) and 2009 (bottom) Keck AO PSF Airy radius and Lorentz semi-major and minor axes lengths from two-component fits. Notice in 2006 how the Airy radius, until the end of the night, tracks the diffraction limit radius of 2.23 pixels = $0.0221''$, drawn as a line. In 2009, the Airy tracks the diffraction radius of 2.204 pixels = $0.0219''$ in the middle of the night.

3. GEMINI NORTH

3.1. December 8, 2008

From one run at the Gemini North 8 m telescope, at $\lambda = 2.12\ \mu$m and $\Delta\lambda = 0.35\ \mu$m on Dec 8, 2008, we fit the images of stars with combinations of Lorentzians, Gaussians, and Airy patterns. Unlike our previous experience on other telescopes, we find the best single function model for the Gemini PSF is a Gaussian, which, like the Lorentzian, can be elliptical,

$$G = I_0 e^{-r^2/2\sigma^2} \tag{3}$$

and the best two-component model is an Airy plus Gaussian, with a consistent Airy pattern. In addition to being a poorer fit based on the residuals, the Airy plus Lorentz model does not yield a consistent Airy pattern. It would appear that the Gaussian merely replaces the Lorentzian as a description of the under-corrected portion of the PSF in most cases. However, an even better model is a three-component fit. Figure 2 shows the three multiple-component fits to the nearly 300 images of 26 stars on one night, Lorentz+Airy, Gaussian+Airy, and Lorentz+Gaussian+Airy.

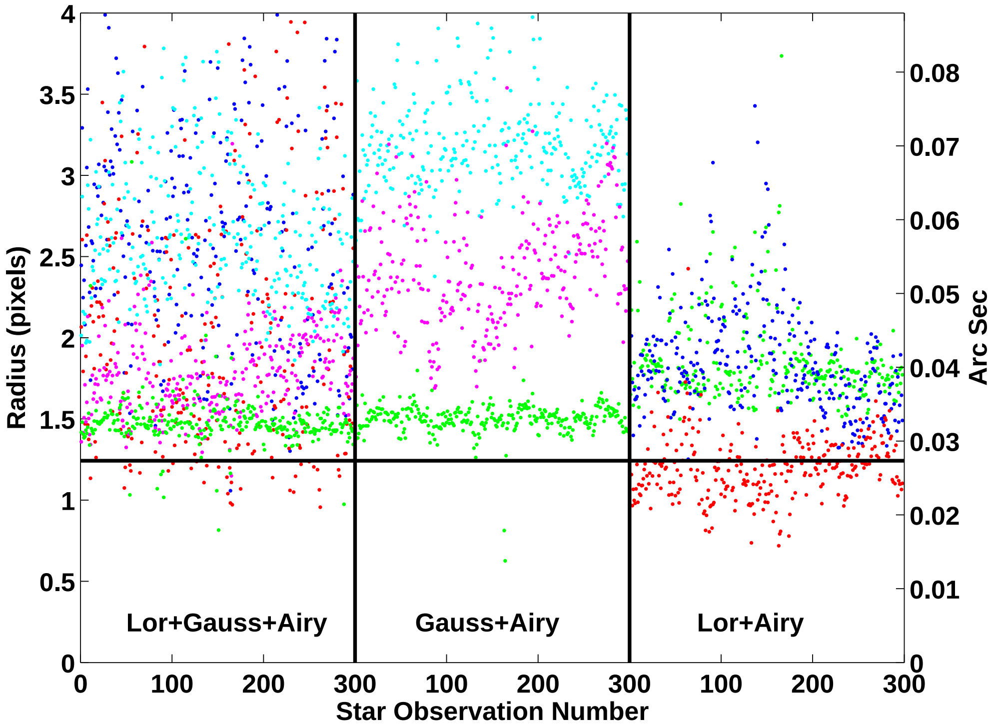

Figure 2. HWHM of models from multi-component fits to Gemini stars. For the Lorentz (at left and right) the semi-major and minor axes lengths are shown in blue and red, respectively, the Gaussian semi-major and minor axes lengths are shown in cyan and maroon (left and center), and the Airy radius is shown in green for all three cases. The diffraction limit radius of 1.23 pixels, or 0.027″, is shown as a line.

With an average Strehl for the 298 images of 0.33±0.05, the median size of the Airy radius found in the three-component model in Fig 2 is 0.032″, and 0.033″ for the Gauss+Airy model, or 19% and 22% greater, respectively, than the theoretical diffraction radius of 0.027″. Thus the Gemini AO is under-performing as indicated by the presence of a Gaussian component.

3.2. February - August, 2009

The Gemini North AO PSF is currently being monitored at the beginning of each observing night when possible. PSFs for 77 nights were obtained over a six month period between February and August 2009. This permitted the PSFs to be measured over a range of seeing conditions and thus a broad range of AO compensation. Each night's observations produced a peak-shifted PSF from which the Strehl ratio was computed. These Strehl ratio normalized PSFs were then co-added for Strehl ratio bins of 0.05 yielding nine distinct averaged PSFs for different levels of AO compensation. Each of the nine binned PSFs were then fit as a Lorentzian, Gaussian, Lorentz+Airy, Gauss+Airy, and Lorentz+Gauss+Airy.

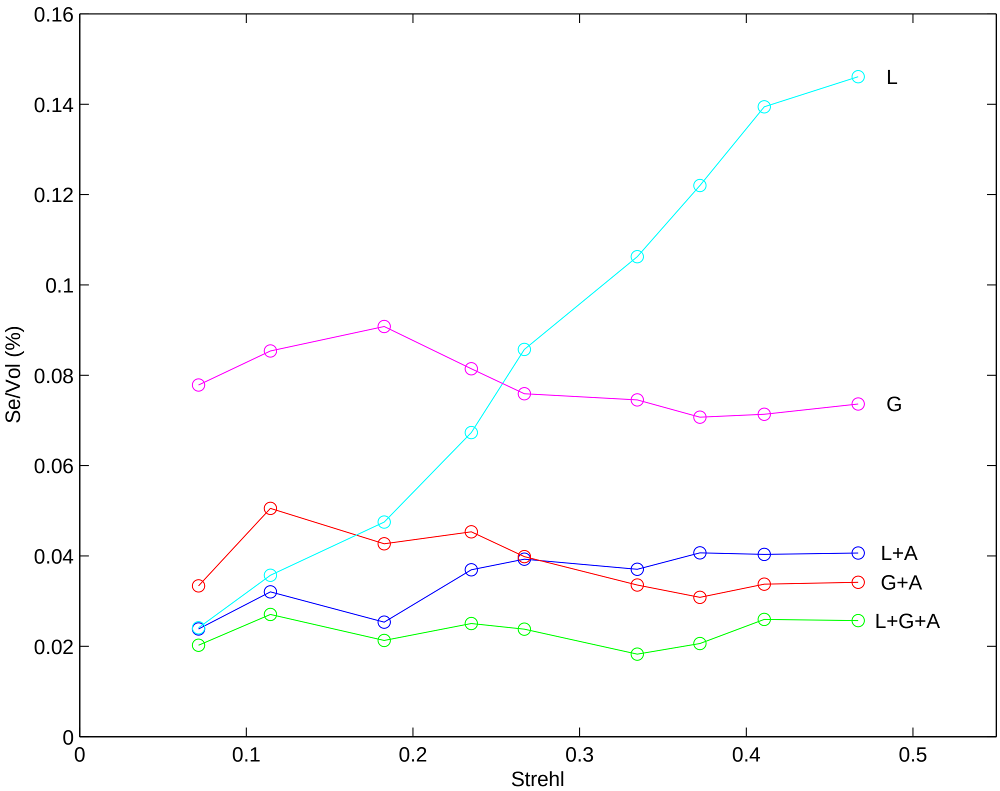

Figure 3. Quality of fit vs Strehl for Gemini 6 month study where 77 stars are gathered into 9 Strehl bins. At the lowest Strehl, including a Lorentzian (L) in the model fit results in a lower standard error of fit, but as the Strehl increases the model with a Gaussian (G) results in a better fit, with the crossover occurring at Strehl ∼0.25. However, the 3-component model always performs best, with 2- and 3-component models including an Airy (A).

This binning by Strehls produces very clean images with little noise, and leads to a clearer picture of Gemini AO performance. Figure 3 shows how the standard errors of fit, normalized to total counts, of the 5 fits vary as a function of Strehl. At the lowest Strehls, the models with the Lorentzians perform the best (lowest ratios), but as the Strehls get better, the models with the Gaussians lead to better fits. The best fit, however, is always the three-component model, which is to be expected since it has more parameters to account for the distribution of signal, 12 compared to 8 for the two-component models.

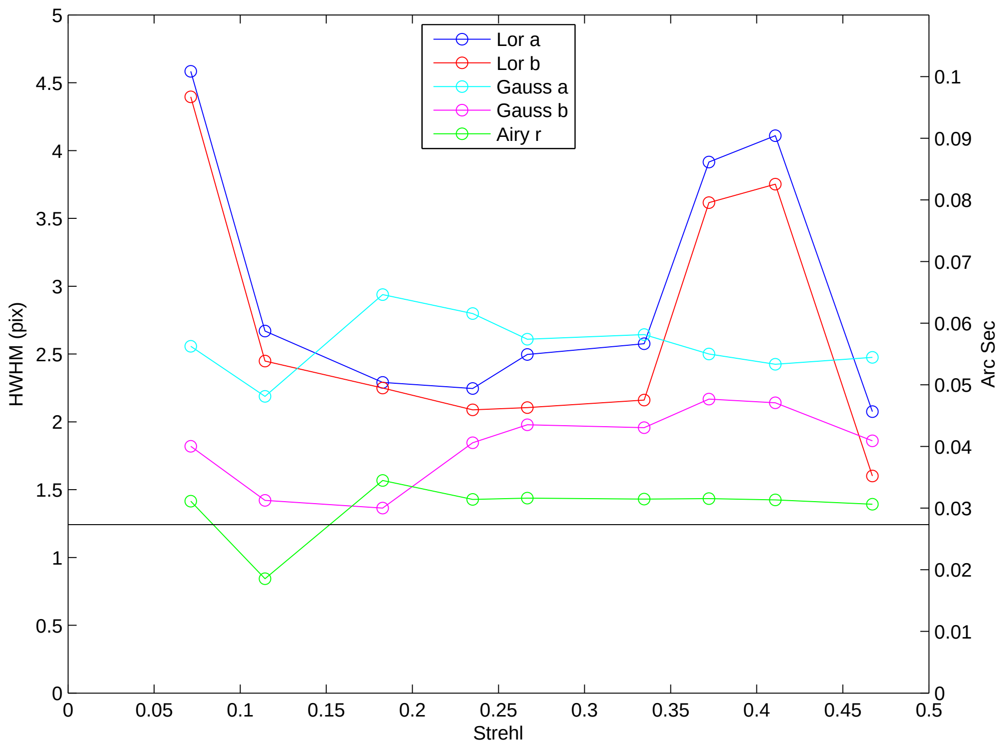

Figure 4. HWHM sizes of components in 3-component model fits of Gemini PSF vs Strehl. The semi-axes of the elliptical Lorentzian and Gaussian components are indicated by a and b. Half the diffraction limit is indicated by the line at 1.23 pixels. The full resolution of the 8 m telescope is not being achieved since the Airy component radius, r, is above this line.

Figure 4 shows how the radii from the three-component fit vary as a function of Strehl, where a and b are the elliptical semi-axes lengths in pixels. The Gauss size varies less than the Lorentzian, indicating a more constant sized component contribution to the under-corrected portion of the signal. The median Airy radius of 1.43 pixels, or 0.031″, still shows that the expected Airy pattern with a radius of 0.027″ is not being reached.

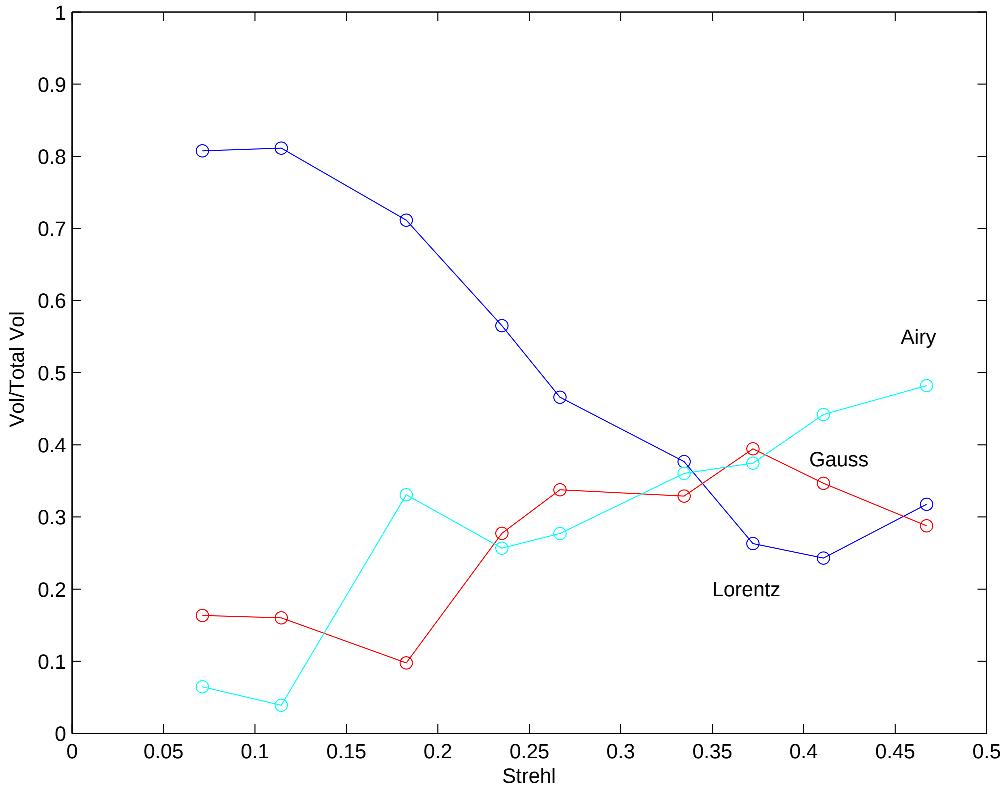

Figure 5. Fraction of total signal in Gemini PSF vs Strehl. The decline and rise of the Lorentz and Airy is understood as competing contributions of the under-corrected and corrected parts of the signal, but the presence of the Gaussian points to an additional anomaly in the Gemini AO system.

To illustrate how much signal is apportioned to the three components, Fig 5 shows the fraction volume of the signal of each component as a function of Strehl. The Lorentz dominates at low Strehls, but as the AO correction gets better, the Airy pattern emerges, as well as a stronger Gaussian component. We expect the Airy and Lorentz behavior with Strehl, since the Airy represents the fully corrected portion and the Lorentz the under-corrected part of the signal, and as one rises the other falls as the Strehl changes. The presence of the Gaussian indicates to us that an additional jitter or error is being added to the AO system.

Figure 6 shows the breakdown of the PSF into its components for the highest and lowest Strehl bins. Again, as the Strehl increases, the Airy component rises, as well as the Gaussian, and the Lorentz declines.

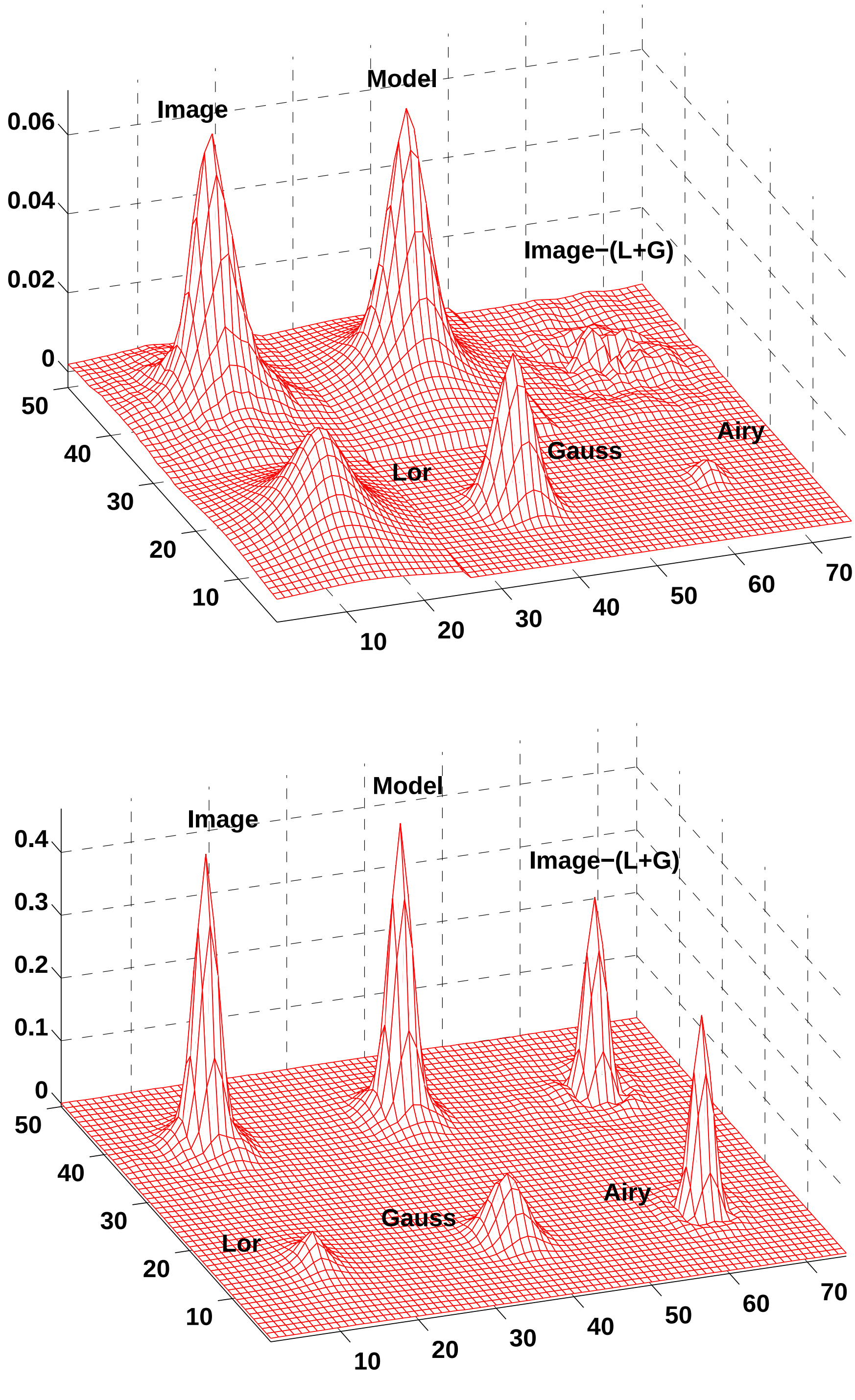

Figure 6. Lowest (S=0.07; top) and highest (S=0.47; bottom) Strehl Gemini PSFs. The 3-component model is shown next to the actual image of the mean star. Shown at the bottom of each case are the three components from the fits. For comparison to the Airy component found in the fit (lower right), the PSF less the Gauss and Lorentz components is shown at upper right for both cases. The plane axes are in pixels.

4. CONCLUSIONS

The canonical picture of an AO PSF is that at low Strehl the Lorentz dominates, and as the Strehl improves, the Airy rises and the Lorentz declines in volume. The PSFs for both the Keck and Gemini AO systems appear to demonstrate this nicely. However, an unexpected Gaussian in the Gemini PSF indicates that an additional abberation is present in the AO system that becomes more evident at higher Strehls.

Moreover, the Gemini AO system suffers decreased resolution (larger than expected Airy), probably because of the presence of the Gaussian component. The excess width of the Gemini PSF is currently being investigated and is most likely due to blurring of the instantaneous PSF by high frequency vibrations caused by the cryocoolers for other instrumentation mounted on the Gemini Cassegrain plate. We predict that when corrected, the Gemini PSF will become more like a Lorentzian, or a Lorentz plus Airy. However, it behooves us to recall that the Gemini AO still improves the resolution over non-AO imaging by more than 25 times, and that overall, the Gaussian component creates only a minor effect.

REFERENCES

1. Conrad, A.R., Dumas, C., Merline, W.J., Drummond, J.D., Campbell, R.D., Goodrich, R.W., Le Mignant, D., Chaffee, F.H., Fusco, T., Kwok, S.A. and R.I. Knight 2006. Direct measurement of the size, shape, and pole of 511 Davida with Keck AO in a single night. Icarus, 191, 616-627.
2. Drummond, J. and Christou, J. 2008. Triaxial Ellipsoid Dimensions and Rotational Poles of Seven Asteroids from Lick Observatory Adaptive Optics Images, and of Ceres. Icarus, 197, 480-496.
3. Drummond, J., Christou, J., and Nelson, J. 2009. Triaxial Ellipsoid Dimensions and Poles of Asteroids from AO Observations at the Keck-II Telescope. Icarus, 202, 147-159.
4. Drummond, J. D. 1998. Adaptive optics Lorentzian point spread function. Adaptive Optical System Technologies, Domenico Bonaccini; Robert K. Tyson; Eds. Proc. SPIE 3353, 1030-1037.
5. Drummond, J.D. 2000. Measuring Asteroids with Adaptive Optics. In: Ageorges, N. Dainty, C. (Eds.), Laser Guide Star Adaptive Optics for Astronomy, Kluwer Academic Publishers, Dordrecht, 243-262.