Figure 7. Ratio of dark-corrected sky flat taken with dust cover closed to dark-corrected sky flat taken with dust cover open. Both images acquired on sol 90. The vignetting at lower left is caused by black tape that was added to the MI dust cover to allow verification of cover state based on image data.

1.05 DN at line 1. Therefore, the maximum calibration error for MI images returned without simultaneous reference pixels (including dark current and offset errors described above) is about 4.2 DN.

2.3. Sky Flats

[12] As described in the MI calibration report [*Herkenhoff et al.*, 2004a], test schedule constraints did not allow flat field images to be acquired after integration of the MI dust cover. It was therefore necessary to determine the flat field sensitivity of the camera/dust cover combination using in-flight data. Images of the Martian sky, or "sky flats," can be used as flat fields [*Reid et al.*, 1999] if variations in sky brightness can be quantified or modeled. To evaluate possible variations in sky brightness over the Opportunity landing site, Navigation Camera (Navcam) [*Maki et al.*, 2003] images were acquired at the same time as MI sky flats, showing the same patch of sky observed by the MI.

[13] The first set of MI/Navcam sky flats were acquired by Opportunity on sol 90, at the end of the primary mission. These sky flats were acquired at a solar scattering angle of 98° and showed no evidence of scattering of sunlight in the optics (Figure 5) and therefore were used to measure the flat field response of the MI with the dust cover open and closed. The MI sky flats were corrected for transfer smear by subtracting a "shutter" image onboard the rover, then corrected for dark current using the reference pixel data returned with the images and a model of the active area dark current. The left Navcam sky flat image was similarly processed and radiometrically calibrated by JPL's Multimission Image Processing Laboratory (MIPL) [*Alexander et al.*, 2006], and the part of the image that viewed the same patch of sky as the MI sky flats was extracted. The Navcam sky flat was then low-pass-filtered to remove noise but preserve the variation in sky brightness across the image, and normalized to the average of the central 101 × 101 pixels. The dark-corrected MI sky flats were then divided by the low-pass-filtered, normalized Navcam sky flat to remove variations in sky brightness. The resulting image shows structure (Figure 6) not observed in preflight calibration data that is unlikely to be due to a change in response across the CCD. The difference between the normalized images shown in Figure 6 has a standard deviation of 0.9%, probably due (at least in part) to dust contamination of the MI optics. MI sky flats acquired on sols 367 and 697 were processed in the same way as the sol 90 sky flat and show similar but not exactly the same structure, perhaps indicating changes in dust contamination.

[14] We have not yet used the in-flight MI sky flats to update the flat field calibration files for the dust cover open state, pending analysis of more recently acquired sky flats. A ratio of the Pancam L3 (673 nm) and L5 (535 nm) [*Bell et al.*, 2003] sky images acquired on sol 697 shows a maximum 4% difference in the sky gradient, so the sky gradient at the Navcam effective wavelength (667 nm) [*Soderblom et al.*, 2008] is likely within 4% of the sky gradient at the MI effective wavelength (the difference in effective wavelength of the Pancam L3 and L5 filters is greater than the difference in the MI and Navcam effective wavelengths). Therefore, low-frequency errors in flat field correction using sky images are probably less than 4%.

[15] In order to determine the flat field response with the dust cover closed, sol 90 sky flats, taken with and without the dust cover, were corrected for dark current. The image taken through the dust cover was then divided by the image taken without the dust cover (Figure 7). MI images taken through the dust cover are radiometrically calibrated using the preflight data described above, then corrected for flat field by dividing by the ratio image. Close inspection of the sky images shows the effects of radiation; these effects have not yet been removed from the ratio image. The standard deviation of the central 101 × 101 pixels in the processed sol 90 sky flats is 3.0%, greater than the 2.8% standard deviation in the same region of preflight flat fields taken at room temperature [*Herkenhoff et al.*, 2004a]. Thermal noise should be less in the sol 90 sky flats (acquired when the CCD was at −5.4°C) than in the preflight flat fields taken under ambient conditions. The increase in noise is therefore probably caused by the radiation effects discussed above. Sky flats acquired on sol 367 (at a solar scattering angle of 120°) were processed in the same way and also have 3.0% noise in the central region. The difference between the sol 90 and sol 367 processed sky flats shows evidence of radiation effects, with a standard deviation of 0.9%. Hence, we use preflight flat field data to correct for pixel-to-pixel sensitivity variations in MI images, with the additional correction for images taken with the dust cover closed. When this calibration method is applied to the sol 90 sky flats, the noise in the central 101 × 101 pixels is reduced to 0.7%. This result indicates that the relative (pixel-to-pixel) radiometric calibration accuracy for this camera is better than 1%, except in localized areas where radiation contributes noise.