Mid-Infrared Imaging of the Bipolar Planetary Nebula M2-9 from SOFIA

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ABSTRACT

We have imaged the bi-polar planetary nebula M2-9 using SOFIA's FORCAST instrument in six wavelength bands between 6.6 and 37.1 um. A bright central point source, unresolved with SOFIA's ~4" beam, is seen at each wavelength, and the extended bipolar lobes are clearly seen at 19.7 μm and beyond. The photometry between 10 and 25 um is well fit by a model of the type previously proposed for this source by Lykou et al and Chesneau et al. The principal new results in this paper relate to the distribution and properties of the dust that emits the infrared radiation. In particular, a considerable fraction of this material is spread uniformly through the lobes, although the dust density does increase at the sharp outer edge seen in higher resolution optical images of M2-9. The dust grain population in the source is unusual in that small (<0.1um) and large (>1um) particles appear to be present in roughly equal quantities by mass. We suggest that collisional processing within the bipolar outflow plays an important role in determining the particle size distribution. These early results show the promise of the SOFIA airborne observatory as a platform for studying planetary nebulae.

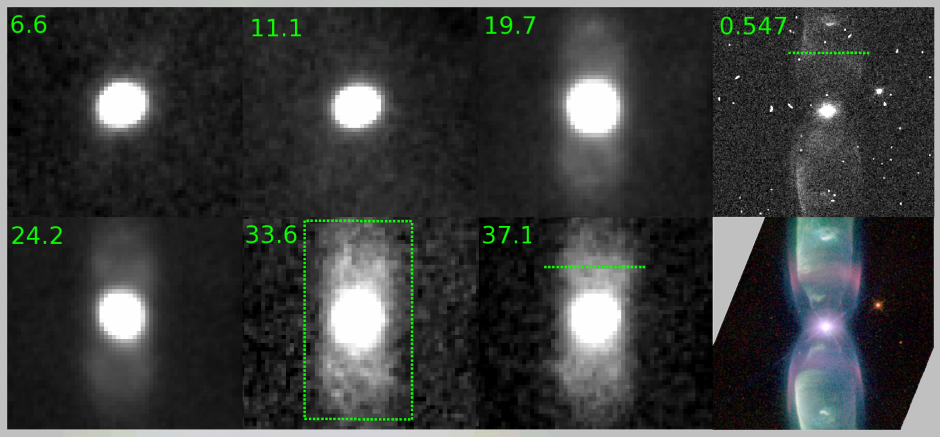

Figure 1 (right): Images of M2-9 at six SOFIA wavelengths, augmented with data from HST in the two right hand panels. The images are oriented with N to the top and E to the left. The rectangle on the 33.6 um image is 20"x40" in size. The dotted lines 10" to the N of the central point source trace the path along which the simulations described in the text were calculated. The HST data, 0.547 nm in the upper right, and a multiband optical emission line image in the lower right, were taken in 1997.

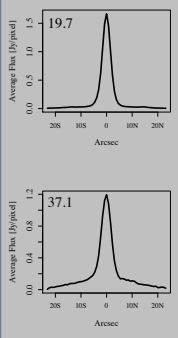

Figure 2 (left): N-S scans through the M2-9 point source at 19.7 [top] and 37.1 um. The data are averaged over 5 pixels (~ 3.8") in the E-W direction at each wavelength.

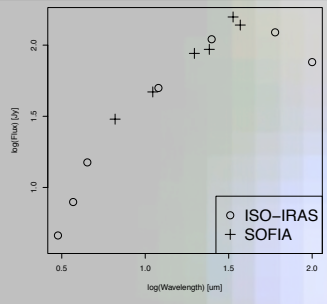

Figure 3: 2.5-120 um SED of M2-9 including data from ISO, IRAS, and SOFIA.

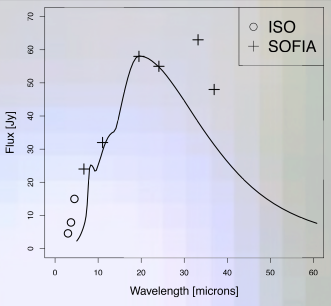

Figure 4: SOFIA and ISO photometry of the central point source of M2-9 compared with the predictions of the model.

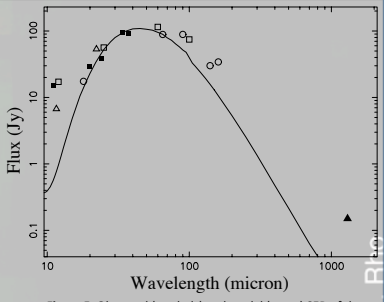

Figure 5: Observed (symbols) and model (curve) SED of the M2-9 lobes. The photometric data shown are as follows: filled squares -- SOFIA, open squares -- IRAS, open triangles -- WISE, open circles -- AKARI, filled triangle -- IRAM 30m. In all cases, the photometry has been corrected for the point source contribution based on the model shown in Figure 4.

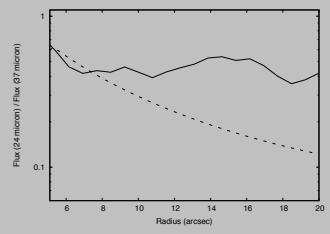

Figure 6: 24.2-to-37.1 um ratio as a function of position N of the central point source. Solid line: Data, averaged over 11 pixels in the E-W direction. Dotted line: Prediction of the DUSTY model in Figure 5.

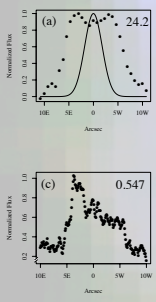

Figure 7: Normalized E-W scans 10" N of the point source through the images of M2-9 at 24.2 (a) and 37.1 (b) um. Overlaid on each SOFIA scan is the beam profile at that wavelength. For comparison, a similar scan through the 547 nm HST image is shown in panel (c). The 37.1 um data is averaged over three N-S pixels, and the HST data over 20 N-S pixels. The relative uncertainty in the SOFIA data is just a few percent, as shown by the small point-to-point scatter.

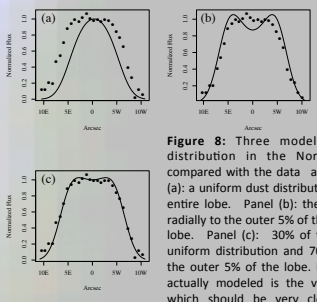

Figure 8: Three models for the dust distribution in the Northern lobe are compared with the data at 37.1 um. Panel (a): a uniform dust distribution which fills the entire lobe. Panel (b): the dust is confined radially to the outer 5% of the optically visible lobe. Panel (c): 30% of the dust is in the uniform distribution and 70% is confined to the outer 5% of the lobe. Note that what is actually modeled is the volume emissivity, which should be very close to the dust distribution as described in the text.

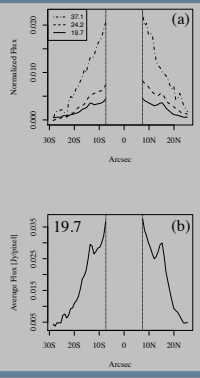

Figure 9: N-S scans along the axis of the M2-9 lobes [cf. Figure 2] are displayed on an expanded scale. In all cases the data are averaged over 5 pixels in the E-W direction. Panel a. (top) shows that the knots ~ 15" N and S of the central point source are detected at 19.7 um but not at 37.1 um; only the northern knot is detected at 24.2 um. Panel b. (bottom) shows the 19.7 um scan in units of Jy/pixel to illustrate the absolute brightness of the emission.

CONCLUSIONS

1. The principal new results from these SOFIA observations of M2-9 center around the spatial and size distribution of the grains which produce the infrared radiation from the outflow lobes in this bipolar nebula. The spatial distribution of the emission implies that the lobes are fairly uniformly filled with dust, with a marked increase in the dust density in a relatively narrow cylindrical annulus -- with width order 5% of the lobe radius -- at the outer edge of the lobes. he result that dust is well mixed over the interior of the lobe is well-established. The side to side asymmetry seen in the HST continuum image of M2-9 is not seen in the infrared images, although it would have been apparent at SOFIA's resolution. The reason for this puzzling discrepancy is unclear, but it may be related to the range of grain sizes which characterize this source; the M2-9 lobes have comparable masses of particles with radii > 1 um and with radii < 0.1 um.
2. At wavelengths from 6.6 to 37.1 um, the image of M2-9 is dominated by a bright central point source, which is not definitely resolved at any wavelength with SOFIA's ~ 4"-to-5" beams.
3. The extended bipolar lobes are clearly seen at wavelengths from 19.7 to 37.1 um; the integrated emission from the lobes is detected down to 6.6 um.
4. The infrared emission of the point source at wavelengths between 11.1 and 24.2 um agrees extremely well with the predictions of a disk model based on Lyk11. The fit suggests a distance of 1200 pc to M2-9 and a luminosity of 2500 L_{sun} for the star which powers it, although the distance and hence the luminosity are not well-constrained. Assuming isotropic emission, we find that the total 2.5-40 um infrared luminosity of the compact source is ~ 840 L_{sun} , and that of the lobes ~ 390 L_{sun} . The total observed 2.5-120 um luminosity of M2-9, including the IRAS measurements at longer wavelengths, and assuming isotropic emission, is ~ 1530 L_{sun}. Because the emission is clearly not isotropic, this is not inconsistent with the 2500 L_{sun} inferred from the disk model. The SOFIA photometry agrees well with that obtained from other platforms, including ISO, WISE and IRAS.

This work is based on observations made with the NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA), operated by USRA and DSI. Portions of the work were carried out at the Jet Propulsion Laboratory, operated by the California Institute of Technology under a contract with NASA.

NASA / DLR / USRA / DSI / FORCAST team / M. Werner et al. / A. Helton, J. Rho