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10-μm imaging of the bipolar protoplanetary nebula Mz-3

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ABSTRACT

A 10-μm image is presented of the bipolar protoplanetary nebula Mz-3 made at the 3.9-m Anglo-Australian Telescope using the NIMPOL mid-infrared imaging polarimeter. The image shows extended emission from warm (110–130 K) dust both to the north and to the south of the central star, which correlates well with the visible bipolar lobes. The observed surface brightness of this emission is consistent with radiative heating of the dust by both direct stellar illumination and trapped Lyman α photons. Emission in excess of the point-source profile indicates that there is also an extended shell of dust surrounding the central star.

Key words: polarization – circumstellar matter – stars: imaging – dust, extinction – planetary nebulae: individual: Mz-3 – infrared: stars.

1 INTRODUCTION

Mz-3 is a bright protoplanetary nebula, appearing in optical images as a bipolar nebula with lobes of total extent ~50 arcsec with a roughly north–south axis (Schwarz, Corradi & Melnick 1992; Scarrott, Scarrott & Wolstencroft 1994). The lobes are bisected by a dark lane which Meaburn & Walsh (1985) suggest is a disc of neutral material around the central source which is expanding at a rate of ~20 km s^{-1}. Cohen et al. (1978) identified the partially obscured central source as a hot star, ~32 000 K and with spectral type O9.5. They calculated the distance to Mz-3 to be ~1.8 kpc, and a lower bolometric luminosity limit of ~5700 L$_{\odot}$, although calculations by Lopez & Meaburn (1983), based on the electron density, suggest that the distance to Mz-3 is <1 kpc. van der Veen, Habing & Geballe (1989) find a luminosity of 1400 × D^2 (kpc) and a distance of 3.3 kpc, implying a total luminosity of 15 000 L$_{\odot}$.

A model of Mz-3 presented by Lopez & Meaburn (1983) suggests that the long axis of the nebula is inclined to the line of sight by an angle of around 30°. Further, they suggest that the bright lobes are a product of successive ejections of material from the outer layers of the star which form radiatively ionized shells. There are purportedly two outer shells to the south of the central source which contain a central spherical cavity that is expanding at v = 50 km s^{-1} (Meaburn & Walsh 1985). In the north the situation is similar, with only one outer shell present. An alternative steady-state model is also presented by Lopez & Meaburn (1983) in which the lobes are due to the collision of an energetic particle wind with surrounding material. Based on a stellar wind velocity of $V_* = 1229$ km s^{-1} the ejection and steady-state models give mass-loss rates of $\dot{M}_* = 1.7 \times 10^{-4}$ and 3.9×10^{-7} M$_{\odot}$ yr^{-1}, respectively.

V-band imaging polarimetry by Scarrott et al. (1994) suggests that the bipolar lobes are filled with hot ionized gas which makes them largely self-luminous at visible wavelengths. These lobes are bounded by dusty shells swept up from the outer layers of the stellar envelope by a fast stellar wind. The shells scatter light from the central star, forming a larger scale visible reflection nebula.

Mid-infrared spectrophotometry by Aitken & Roche (1982) of Mz-3 shows a relatively featureless 8–13 μm spectrum aside from an emission line at 12.8 μm attributed to Ne II. They found a good fit to the 10-μm spectrum of Mz-3 with a featureless continuum affected by absorption due to overlying colder silicate grains. Based on the infrared excess when compared to a fitted blackbody curve, Cohen et al. (1978) calculated a temperature of $T = 900 \pm 30$ K for the central portion of the nebula. As part of a more extensive study of the dust in protoplanetary nebulae, we have carried out 10-μm imaging of Mz-3 to determine the spatial extent of warm dust around the central source and in the lobes.

2 OBSERVATIONS

The observations were made at the 3.9-m Anglo-Australian Telescope (AAT) on 1995 August 10, using the NIMPOL

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mid-infrared imaging polarimeter built in the School of Physics, University College at the Australian Defence Force Academy (Smith, Aitken & Moore 1994). NIMPOL uses a 128×128 element, Si:Ga focal-plane array which has 0.25-arcsec pixels and a 32-arcsec field of view when mounted at the Cassegrain focus of the AAT with the $f/36$ chopping secondary. The images were obtained through a broad-band 8–13 μm filter using polarimetry mode, i.e. with a warm rotating CdS half-wave plate and a cold wire-grid analyser in the beam.

Mz-3 was observed for a total on-source time of 31 min, using a 12-arcsec north–south chop throw and a 12-arcsec east–west beamswitch with all four positions within the field of view. After shifting and adding sets of frames to remove telescope motions occurring on a time-scale of ~ 100 s, the effect of the short chop on the overlapping extended emission was removed by using the northern pair of the four images in the field (produced by the chop-nod pattern) to reconstruct the two southern images. These two restored images were then coadded to produce a final image of Mz-3. Effective on-source integration times are thus 16 min for the extended lobes.

Flux calibration was obtained from matching observations of the mid-infrared standards BS6832 [η Sgr; $S(10\,\mu\mathrm{m}) = 197$ Jy], BS8636 [β Gru; $S(10\,\mu\mathrm{m}) = 933$ Jy] and BS7525 [$S(10\,\mu\mathrm{m}) = 93$ Jy], and has an estimated uncertainty of 10 per cent. Mz-3 was observed at an airmass range of 1.08–1.13. The polarization standard was the BN object in Orion, assumed to have a polarization angle of 118° at 10 μm.

3 RESULTS AND DISCUSSION

The 10-μm grey-scale image of Mz-3 is presented in Fig. 1. The image shows a bright central source with extended emission to the north and a fainter extended emission to the

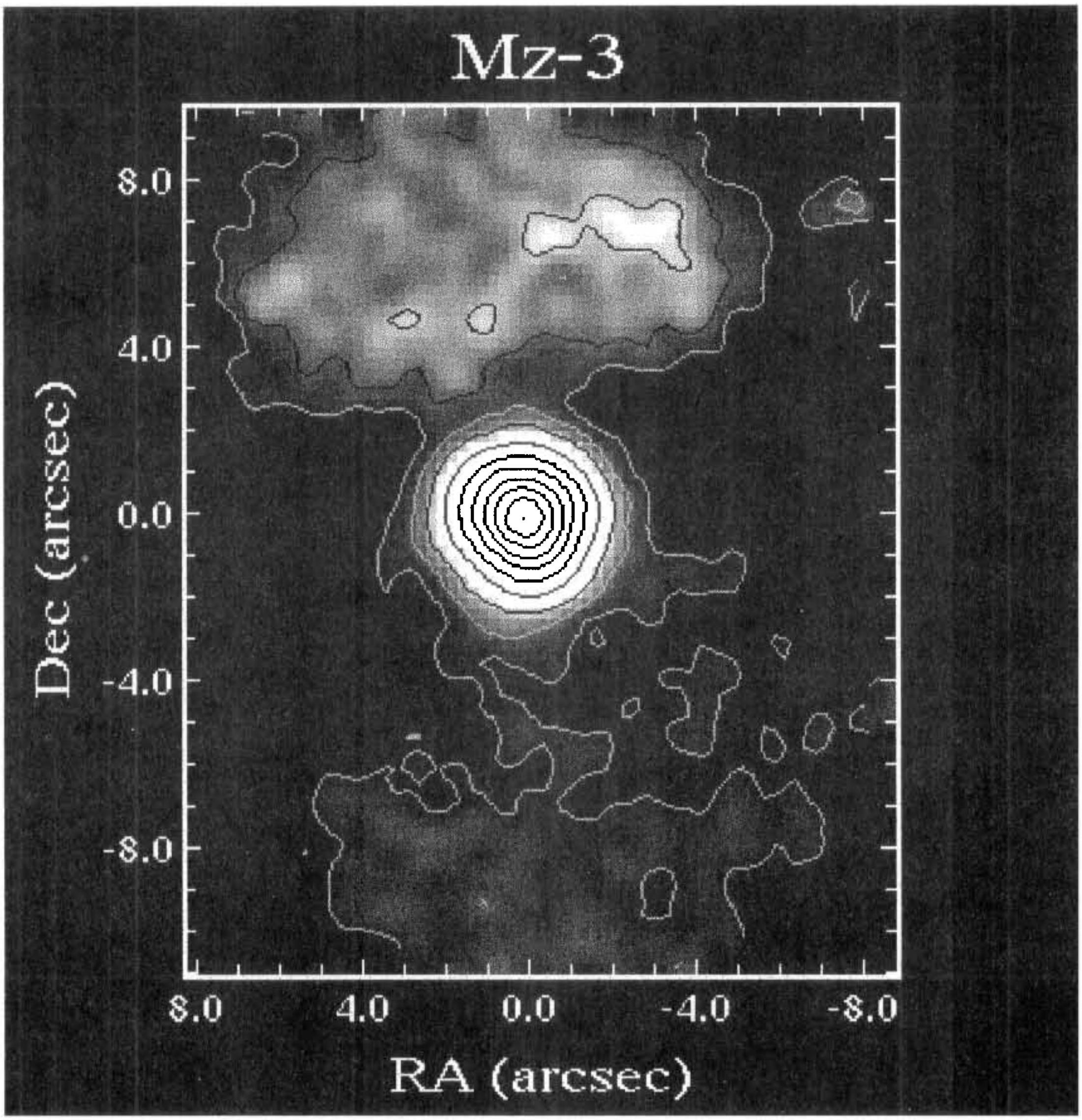

Figure 1. A smoothed 10-μm grey-scale image of Mz-3 with contours at 90, 190, 350, 750, 1310, 2080, 3120, 4480, 6080 and 8000 mJy pixel^{-1}. Offset zero is at $16^{\mathrm{h}}13^{\mathrm{m}}23\overset{\mathrm{s}}{.}4$, $-51°51'47''$(1950).

south, with similar morphology to the visible images of Cohen et al. (1978), Schwarz et al. (1992) and Scarrott et al. (1994). The similarity between the visible and infrared images suggests that the dust seen in emission at 10-μm is the same dust that is scattering at visible wavelengths. There is an apparent maximum in the extended emission around 7 arcsec to the north of Mz-3, but the separation to the southern extended emission lobe is less well defined. The mean surface brightness of the northern emission in the image is 270 mJy arcsec^{-2} while in the south it is 100 mJy arcsec^{-2}, with rms noise levels of 40 mJy arcsec^{-2} for each. The oversampled image is smoothed using a Gaussian function with $\sigma = 1.5$ pixel, although the seeing was closer to 1 arcsec. The smoothed image has noise levels of ± 8 mJy arcsec^{-2}.

In a 5-arcsec, circular software aperture, the central bright source in Mz-3 has a flux density of 29 Jy through the broad-band 10-μm filter, with a calibration error of ± 3 Jy and signal-to-noise ratio of 116. This flux density is consistent with the results obtained by van der Veen et al. (1989) and Aitken & Roche (1982).

These observations did not produce a significant detection of polarization in Mz-3. Again using a 5-arcsec circular software aperture, we obtained formal values of 1.2 ± 1.2 per cent at $69° \pm 29°$ for the polarization and position angle (east of north), respectively. The position angle is, however, consistent with previous determinations in the visible (position angle $\sim 70°$) by Scarrott et al. (1994) for the direction of interstellar polarization at the central source.

A nebula with the stellar luminosity and size of Mz-3 is likely to have a low optical depth at 10 μm and the grains will be heated both radiatively and by trapped Lyman α photons in the ionized gas filling the bipolar lobes (Pottasch 1987). For dust at 7 arcsec from the central source (the apparent maximum of the extended emission), and assuming that in Mz-3 the ratio of the ultraviolet and infrared absorption coefficients is ~ 100 and that $n_e M_g / M_d \sim 2 \times 10^7$ cm^{-3}, where n_e is the electron density and M_d / M_g is the dust-to-gas mass ratio then, from fig. 2 of Pottasch (1987), a planetary nebula with luminosity and radius similar to that of Mz-3 would have a dust temperature of around 110–130 K. The observed 10-μm surface brightness in the northern extended lobe of Mz-3 of 270 mJy requires blackbody-equivalent temperatures of $T_d \geq 95$ K to produce this level of emission. If the 10-μm dust optical depth is low, this is consistent with radiative and trapped Lyman α heating of the dust.

The expected 8–13 μm flux density of a 32 000 K stellar photosphere, using a luminosity of $1400 \times D^2$, would be ~ 2 mJy. The stellar photosphere therefore does not contribute significantly to the observed flux density of 29 Jy in a 5-arcsec aperture. Apart from warm dust, the only other possible source of 10-μm flux is free–free emission but, using the measured flux density of 630 mJy for Mz-3 at 5 GHz (Pottasch et al. 1984), the contribution from free–free emission at 10 μm should be no more than 260 mJy across the whole source. It is therefore reasonable to assume that all of the 8–13 μm emission from both the central source and the extended lobes is due to a dust shell around the central star.

Profiles of Mz-3 through the RA and Dec. directions are shown in Fig. 2. The reference curve in both figures is a composite from the images of the three standard stars observed on the same night, all of which are known to be point sources, i.e. it represents the effective point-spread function due to the telescope and atmospheric seeing. Mz-3 shows emission slightly in excess of the average point-source profile at all radii but the majority of the 10-μm emission comes from a region smaller than the spatial resolution of the image. The inner edge of the circumstellar dust shell is therefore unresolved.

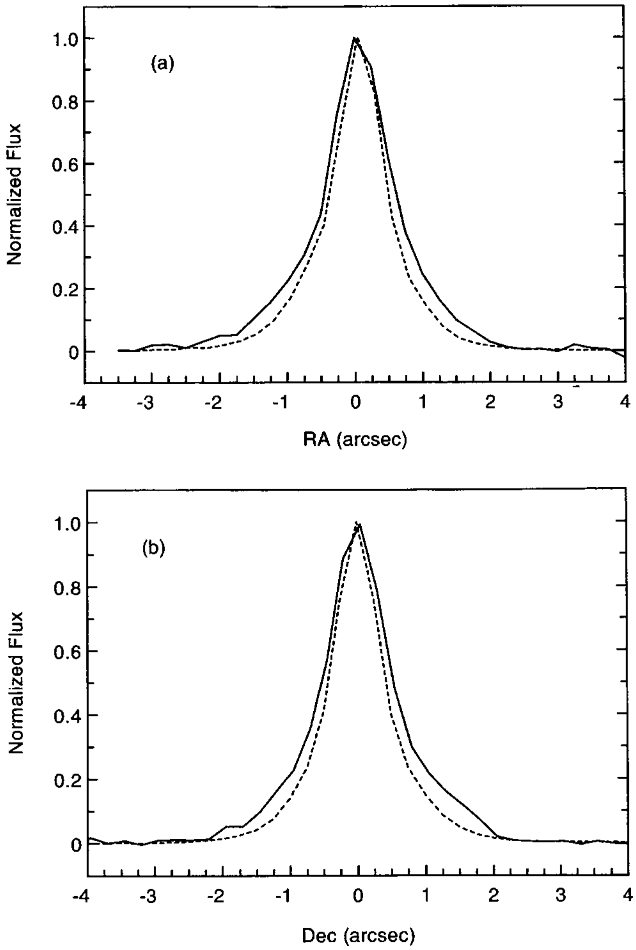

Figure 2. Line profiles of the central source of Mz-3 in (a) RA and (b) Dec. directions through the peak. The solid lines are those of Mz-3, and the dashed lines are a composite of line profiles of the three standard stars observed on the same night.

Assuming continuing, constant mass loss, the inner edge of the dust shell should occur where the equilibrium temperature falls below the condensation temperature for silicates of approximately 1000 K (e.g. Schutte & Tielens 1989). Assuming $T_* = 32\,000$ K and $L_* = 1400$ L$_\odot$ kpc^{-2}, this distance can be approximated to be around 0.02 arcsec from the central star based on a λ^{-1} emissivity and for grains much larger than the wavelength of stellar radiation and much smaller than the wavelength of the emitted radiation from the surrounding dust (Herman, Berger & Pennix 1986). If the mass-loss rate has decreased, the inner shell radius may not be defined by the dust condensation temperature and may be larger than 0.02 arcsec. Since it remains unresolved, however, the inner radius of the dust shell must lie somewhere between ~ 0.02 and ~ 0.2 arcsec from the star, which is ~ 70 to 700 au, if the distance to Mz-3 is 3.3 kpc.

The outer edge of the dust shell at ~ 1.5 arcsec (based on 10 per cent of the emission at the peak) should be at a temperature of $T_d \gtrsim 160$ K if directly radiatively heated. The temperature of 900 K estimated by Cohen et al. (1978) from the 1–4 μm emission spectrum must therefore arise from a dust component close to the inner edge of the circumstellar dust shell, seen either by scattering or directly through an optically thin outer shell.

In summary, 10-μm imaging of Mz-3 shows extended emission from dust to both the north and the south of the central star, which correlates well with the visible bipolar lobes. The observed surface brightness of this emission is consistent with the dust in the lobes being radiatively heated by both Lyman α photons and directly by the central source. The presence of an extended shell of dust surrounding the central star is suggested by emission in excess of the point-source profile.

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