Rings and haloes in the mid-infrared: the planetary nebulae NGC 7354 and NGC 3242

J. P. Phillips,1⋆ G. Ramos-Larios,1⋆ K.-P. Schröder2⋆ and J. L. Verbena Contreras2⋆

1Instituto de Astronomía y Meteorología, Av. Vallarta No. 2602, Col. Arcos Vallarta, C.P. 44130 Guadalajara, Jalisco, México
2Departamento de Astronomía, Div. CNyE, Universidad de Guanajuato, A.P. 144, Guanajuato, C.P. 36000, México

ABSTRACT

We present images of the planetary nebulae NGC 7354 and NGC 3242 in four mid-infrared (MIR) photometric bands centred at 3.6, 4.5, 5.8 and 8.0 μm, the results of observations undertaken using the Spitzer Space Telescope. The resulting images show the presence of a halo and rings in NGC 3242, as previously observed through narrow-band imaging at visual wavelengths, as well as evidence for a comparable halo and ring system in NGC 7354. This is the first time that a halo and rings have been observed in the latter source. Similarly, whilst partial rings may have been previously detected in the MIR (for the source NGC 3132), the present observations appear to constitute the first detections of complete ring systems outside of the visual wavelength regime. The halo/core emission ratios appear to be preferentially higher at MIR wavelengths than is the case in the visible, and show less steep fall-offs than those observed in the [OIII] λλ4959 + 5007 Å transitions. The variation in surface brightness S with radial distance R, where this is approximated by the power-law relation $S \propto R^{-\beta}$, implies exponents $1.7 < \beta < 4$ in the inner portions of the haloes, and $4.5 < \beta < 12$ towards the outer limits of these structures. The value of $\beta$ is also, in most cases, somewhat smaller at longer wavelengths.

It is additionally noted that the 3.6 μm/4.5 μm, 5.8 μm/4.5 μm and 8.0 μm/4.5 μm flux ratios increase markedly away from the nuclei, and reach their maximum values in the haloes, where much of the longer wave flux may derive from dust band and continuum emission. An analysis of the rings suggests that some of them, at least, are likely to be associated with higher densities of dust particles, and that the gaseous and particle ring systems are likely to be spatially in register.

Finally, we have analysed the formation of haloes as a result of radiatively accelerated mass loss in the AGB progenitors. Although the models assume that dust formation occurs in C-rich environments, we note that qualitatively similar results would be expected for O-rich progenitors as well. The model fall-offs in halo density are found to result in gradients in halo surface brightness which are similar to those observed in the visible and MIR.

Key words: stars: AGB and post-AGB – ISM: jets and outflows – planetary nebulae: individual: NGC 3242 – planetary nebulae: individual: NGC 7534 – infrared: ISM.

1 INTRODUCTION

The envelopes of planetary nebulae (PNe) undergo various marked changes during their brief evolutionary lifetimes. Thus for instance, as central stars evolve to higher temperatures, and the fluxes of ionizing photons increase, then D-type ionization fronts are expected to advance into the inner portions of the asymptotic giant branch (AGB) envelopes. This leads to appreciable changes in the pressure and density characteristics of these regimes, and wipes out much of the evidence relating to later phases of AGB mass loss (e.g. Mellema 1994; Meijerink, Mellema & Simis 2003; Perinotto et al. 2004; Schönberner et al. 2005).

Subsequent interaction of the envelopes with fast radiatively driven stellar winds then leads to high temperature bubbles of shocked stellar wind, together with denser, lower temperature regimes of shocked AGB plasma, the latter constrained by a
Figure 1. Comparison of HST, 2MASS and Spitzer images of the central regions of NGC 7354 and NGC 3242, where the HST image for NGC 3242 is from http://www.spacetelescope.org/images/html/opus9738c3.html, and the other results have been processed by the authors using online 2MASS and HST data bases, and the present SST results. For the case of the HST image of NGC 3242, blue emission corresponds to He II λ 4686 Å, green represents the [O II] λ 5007 Å transition and red is [N II] λ 6583 Å, whilst for the HST image of NGC 7354 we have designated [N II] λ 6583 Å emission by red, λ 5410 Å continuum emission by green and [O III] λ 5007 Å transition as blue. The J, H and Ks 2MASS results are represented as blue, green and red, whilst the 3.6, 4.5, 5.8 and 8.0 μm Spitzer results are denoted by blue, green, orange and red, respectively. Note that all of the images are directly comparable with each other, having as they do identical scales, positioning and orientation. Similarly, the 2MASS and Spitzer images have been processed using unsharp masking techniques, leading to sharper representations of fainter nebular structures. Particular points to note include the presence of FLYERS in both sources, delineated by the red [N II] components of emission in the HST images, and including jet-like features at the limits of the major axes. Some of these have been labelled. A few of the FLYERS may also have been detected in the 2MASS and Spitzer images of the sources. It is clear that both sources also have similar morphologies at all wavelengths, consisting of an elliptical inner rim and enveloping shell. The outer halo of NGC 3242 is visible in the lower right-hand panel, where it and the rim and shell features are explicitly labelled.

contact discontinuity at smaller radii, and a forward leading shock (e.g. Schönberner & Steffen 2002; Schönberner et al. 2005). Evidence for these bubbles has become apparent from X-ray observations by the Chandra observatory, whence it is clear that temperatures are of the order of several millions of degrees (e.g. Kastner et al. 2008; Yu et al. 2009).

As the shells expand further, leading to lower mean plasma densities, and the central star evolves to even higher effective temperatures, then ionization of the remaining AGB envelope occurs over time-scales of \( \sim \) a few \( \times 10^5 \) yr (Steffen & Schönberner 2003), and leads to the triple-shelled configuration noted in many more evolved PNe. The nebulae contain an inner bright rim, the fruits of interaction with the stellar wind; an inner shell surrounding this rim, the artefact of earlier ionization by D-type fronts; and a more extended halo representing the original AGB mass-loss envelope (see e.g. Fig. 1, where the rim, shell and halo of NGC 3242 are explicitly labelled). However, this is by no means the final word in the evolution of the shells.

Eventually, a critical phase is reached at which central star hydrogen burning stops, stellar luminosities and temperatures decline, and there occurs a precipitous reduction in the fluxes of ionizing photons. This leads to a contraction of the Stromgren regime within which ionization occurs, and the development of recombination haloes, such as have been previously described by Tylenda (1986), Corradi et al. (2003b) and Phillips (2000). Such recombination haloes can easily be confused with the more normal AGB haloes described above, although they normally occur where shell surface brightnesses are lower, levels of nebular excitation are reduced, Zanstra temperatures are small and \( T_Z(\text{H I}) \cong T_Z(\text{He II}) \). They also lead to ’haloes’ which are brighter than the more common-or-garden AGB haloes described above.

Subsequent evolution of the shells eventually leads to very low densities, comparable to the densities of the interstellar medium (ISM), and this may lead to distortion and disintegration of the envelopes through shearing and hydrodynamic instabilities (see our further comments below).

The AGB haloes have relatively low densities compared to the inner shells and nebular rims, and this may imply that they are in non-thermodynamic equilibrium, and have high electron temperatures (e.g. Marten 1993; Monreal-Ibero et al. 2005). It has also been noted that whilst the inner shells have surface brightness of the order of \( \sim 0.1–0.01 \) those of the inner nebular rim, the brightnesses of the outer haloes is an order of magnitude less, of the order of \( < 2 \times 10^{-3} \) peak nebular values. Most of the haloes are found to be circularly symmetric, or very slightly elliptical (e.g. Hsia, Li & Ip 2008). Exceptions to this occur where the envelopes interact with the ISM, however, a process which results in distortion of the shells, the formation of bright low-excitation rims at the leading edges of the haloes, and displacement of the central stars from the geometrical centres of the envelopes [see e.g. (Tweedy & Kwinter 1994, 1996) for observational results, and Villaver, Manchado & García-Segura 2000, Soker & Zucker 1997, Dgani & Soker...
been suggested that the magnetic dynamo cycle in AGB stars would
90, although it has startlingly similar to those observed for He 2
magnetic field, and where the stellar wind is also magnetized, then
out that where there are changes in the polarity of the progenitor
similar to those observed in young PNe.
Such rings have been detected as reflection artefacts in the neu-
tral shells of young and proto- PNe, where they appear to arise
from spherically symmetric enhancements in the density of out-
flooding dust (viz. the cases of CRL 2688, Sahai et al. 1998; IRAS
17441−2411, Su et al. 1998; IRAS 17150−3224, Kwok, Su &
Hrivnak 1998; IRAS 16594−4656, IRAS 20028 + 3910, Hrivnak,
Kwok & Su 2001). Such regions are also present in the ionized
haloes of more evolved PNe as well, and have been detected in
at least eight nebular outflows, and a possible further four sources
as well (viz. Terzian & Hajian 2000; Corradi et al. 2004). The
nature of these rings is rather poorly defined, although it is clear
that they are relatively faint, and have surface brightnesses which
are no more than ∼15 per cent of those of the underlying haloes
(e.g. Corradi et al. 2004; Hb 5 is an exception in that the ring-
to-halo ratio is of order unity). The density enhancement of the rings
compared to the inter-ring regime has also been found to vary
from factors of ∼2 (Kwok, Su & Stoess 2000) to as high as ∼10
(Mauron & Huggins 1999). Apart from this, our knowledge of the rings is relatively cursory, although at least one PNe (NGC 6543)
has been investigated in greater depth (Balick, Wilson & Hajian
2001; Hyung et al. 2001). The results for this source are not in
all cases consistent, however. Thus, Balick et al. (2001) determine
that the surface brightness properties of the rings can be modelled
in terms of individual shells having negligible amounts of inter-
vening gas. They also determine that electron temperatures within
this regime are relatively normal, although linewidths are unusu-
ally broad (see also Bryce et al. 1992). Hyung et al. (2001), by
contrast, find electron temperatures which are significantly larger,
a phenomenon which may, if confirmed, arise from the formation
processes responsible for the rings.
Despite the short observational history of this phenomenon, how-
erver, and the lack of evidence concerning the physical properties
of the rings, there have nevertheless been several suggestions as to
how such features might form.
Thus for instance, Simis, Icke & Dominik (2001) and Meijerink
et al. (2003) have analysed viscous momentum coupling between
outflowing gas and dust, an analysis in which dust grains are per-
mitted to drift with respect to the neutral AGB envelope. The
results show that spherically symmetric regions will develop in which
dust-to-gas ratios are enhanced, and lead to results which are closely
similar to those observed in young PNe.
Garcia-Segura, Lopez & Franco (2001), on the other hand, point
out that where there are changes in the polarity of the progenitor
magnetic field, and where the stellar wind is also magnetized, then
this would lead to pressure oscillations which drive circularly sym-
metric compressions into the outflowing winds. Their results are
startlingly similar to those observed for He 2−90, although it has
been suggested that the magnetic dynamo cycle in AGB stars would
be much shorter than that corresponding to the rings (Meijerink et al.
2003).
Mastrodemos & Morris (1999) point out that mass loss within
central binary systems has the potential to lead to spiral shocks, and,
again, to ring-like density enhancements similar to those observed
in many PNe, whilst such features may also derive from relaxation
oscillations within the progenitor (Van Horn et al. 2003), solar-
type cycles in magnetic activity (Soker 2000) and variations in the
periods of variability in the AGB progenitors (Zijlstra, Bedding &
Mattei 2002). Icke, Frank & Heske (1992) suggest a process in
which the oscillatory pumping in the interior layers of an AGB star
leads to multiperiodicity or chaotic motion in the surface layers,
although it is not clear if this can really account for the observed
periodicity of the rings (Soker 2000). Similarly, Harpaz, Rappaport
& Soker (1997) have proposed that the periastron passage of a stellar
companion might modulate progenitor mass-loss rates, although
it seems that the exact circularity of the predicted rings may be
inconsistent with observations (Sahai et al. 1998).
There is no over-riding mechanism which can be claimed to be
uniquely in accord with the properties of the rings – most of them,
for instance, indicate similar ring/halo surface brightness ratios. It
seems clear however that the periodicities and time-scale of the rings
are inconsistent with mechanisms based on helium shell flashes,
since the typical interflash period is ∼104 yr (Kwok et al. 1998;
Sahai et al. 1998).
An interesting consequence of certain models, such as those of
Simis et al. (2001) or Mastrodemos & Morris (1999), is that a
Drift of grains with respect to the gas might be expected to lead
to positional decoupling of the dust and gaseous rings. Where
the grains are responsible for warm dust continua, or, say, give
rise to polycyclic aromatic hydrocarbon (PAH) emission bands,
then infrared emitting rings might be displaced from their gaseous
counterparts (as observed through narrow-band Hα, [N ii] or [O iii]
imaging). Alternatively, where 3.6 and 4.5 μm emission is asso-
ciated with gaseous components of emission, as appears to be the
case in many PNe (e.g.Hora et al. 2004; Phillips & Ramos-Larios
2008a,b; Ramos-Larios & Phillips 2008), but the 5.8 and 8.0 μm
fluxes are dominated by emission from small PAH emitting grains,
then yet again, one might see some evolution in ring placement
and structure on passing from shorter to longer mid-infrared (MIR)
wavelengths. We shall investigate such possibilities in our analysis
below.
Previous MIR observations of partial ring structures have been
reported for the case of NGC 3132 (Hora et al. 2004). We report
here the further MIR observation of more complete ring systems
in NGC 3242 and NGC 7354. The rings in NGC 3242 were first
discovered in the [O iii] and Hα + [N ii] imaging of Corradi et al.
(2003, 2004). In the case of NGC 7354, by contrast, it was concluded
that there was little evidence for a halo down to ∼2 × 10−3 peak
nebular intensity (Corradi et al. 2003). Our present results will show
that this source does have a halo, and that the halo also contains
rings.
It will be noted that the strength of the halo emission (when
compared to peak core fluxes) is ∼10 times greater than is observed
for optical permitted and forbidden line transitions. This argues for
markedly differing emission mechanisms in the MIR from those
prevailing in the visible.
Finally, we shall note below that the fall-off of halo emission at 3.6
and 4.5 μm appears to consist of two main trends: an interior fall-off
in surface brightness S ∝ r−β, where β ∼ 1.4 → 4, corresponding to
the regime where the rings themselves appear to be located, followed
by a much steeper decline in which β ∼ 6.3 → 12. The fall-off at
longer wavelengths tends to be qualitatively similar, although with values of $\beta$ which are somewhat less. The possible origins of these gradients are discussed in Section 4.

2 OBSERVATIONS

We shall be making use, in the following analysis, of data products deriving from Spitzer Space Telescope (SST) program 30285 ('Spitzer observations of PNe 2'), the near-infrared (NIR) Two-Micron All-Sky Survey (2MASS), and Hubble Space Telescope (HST) programme 8773 undertaken using the Wide Field Planetary Camera 2 (WFPC2).

The Spitzer observations of NGC 3242 and NGC 7354 took place on 2006 December 29 and 2006 August 9, after which the raw results went through various stages of analysis as described in the Infrared Array Camera (IRAC) data handbook (available at http://ssc.spitzer.caltech.edu/irac/iracdatahandbook_3.0.pdf). The first of these processes results in the so-called Basic Calibrated Data (BCD). In this case, the raw observations are converted into an appropriately flux-calibrated image, and the primary instrumental defects are removed. A further stage of processing (post-BCD) was then undertaken using a specific, conservative set of parameters, and included geometric corrections to the images – the removal of defects which are not based on well-established instrumental artefacts or detector physics. A so-called pointing refinement is also undertaken, whereby point sources within the fields are astrometrically matched to sources in the 2MASS catalogue, whilst mosaics are produced from the multiple Astronomical Observation Requests (AORs; in the case of Program 30285, this involved combining 14 BCDs for each of the nebulae investigated here).

The present results all correspond to post-BCD products and are, as a result, relatively free from artefacts, are well calibrated in units of MJy sr$^{-1}$ and have reasonably flat emission backgrounds. An exception to this are the weak central horizontal emission bands at 8.0 $\mu$m caused by the bright central cores. We have not removed these from the present results, since they have little impact upon the analysis or its interpretation. They do however need to be considered when obtaining profiles through the source.

The observations were taken using the IRAC (Fazio et al. 2004), and employed filters having isophotal wavelengths (and bandwidths $\Delta \lambda$) of 3.550 $\mu$m ($\Delta \lambda = 0.75 \mu$m), 4.493 $\mu$m ($\Delta \lambda = 1.9015 \mu$m), 5.731 $\mu$m ($\Delta \lambda = 1.425 \mu$m) and 7.872 $\mu$m ($\Delta \lambda = 2.905 \mu$m). The normal spatial resolution for this instrument varies between $\sim$1.7 arcsec and $\sim$2 arcsec (Fazio et al. 2004), and is reasonably similar in all of the bands, although there is a stronger diffraction halo at 8 $\mu$m than in the other IRAC bands. This leads to differences between the point source functions (PSFs) at $\sim$0.1 peak flux. The observations were obtained in 2006 August (NGC 7354) and 2008 January (NGC 3242), correspond to post-BCD and have a spatial resolution of 1.2 arcsec pixel$^{-1}$.

We have used these data to produce colour-coded combined images of the sources in the four IRAC bands, where 3.6 $\mu$m is represented as blue, 4.5 $\mu$m as green, 5.8 $\mu$m as orange and 8.0 $\mu$m is indicated by red. Several of these results have also been processed using unsharp masking techniques, whereby a blurred or ‘unsharp’ positive of the original image is combined with the negative. This leads to a significant enhancement of higher spatial frequency components, and an apparent ‘sharpening’ of the image (see e.g. Levi 1974). Profiles through these sources have also been produced with the aim of evaluating the fall-off in surface brightness of the halo structure. This involved an initial correcting for the effects of background emission, a component which is present in all of the bands, but is particularly strong at 5.8 and 8.0 $\mu$m. The latter two bands are also prone to slight gradients in the background of the order of $5 \times 10^{-4}$ MJy sr$^{-1}$ pixel$^{-1}$ (although actual gradients vary depending upon the source and waveband under consideration, and the direction of the slice). We have removed these trends by subtracting linear ramps from the results – a procedure which is more than adequate given the limited sizes of the nebulae. Both of the sources also suffer from weak central emission bands at 8 $\mu$m, as described above (although this is barely visible in the case of NGC 7354). The strength of this contaminant is low ($\sim$0.4 per cent of peak emission fluxes), however, and tends to be constant with x-axis displacement. We have chosen slices through the nebula which minimize the impact of this feature, and the band is likely to have zero-to-negligible influence upon our present results.

The results were subsequently processed so as to indicate the variation of 3.6 $\mu$m/4.5 $\mu$m, 5.8 $\mu$m/4.5 $\mu$m and 8.0 $\mu$m/4.5 $\mu$m ratios with distance from the nucleus. The rationale behind this is based on the fact that many PNe possess strong PAH emission bands at 3.3, 6.2, 7.7 and 8.6 $\mu$m, located in the 3.6, 5.8 and 8.0 $\mu$m IRAC bands. Furthermore these features, and their associated plateau components, show evidence for increased strength outside of the nebular cores, in the halo regions of interest to our present analysis. Given that the 4.5 $\mu$m band is usually dominated by bremsstrahlung continua and a variety of molecular and ionic transitions, it then follows that the variation of these ratios gives some insight into the importance of PAH emitting grains (see e.g. Phillips & Ramos-Larios 2008a,b).

We have also obtained contour mapping of the 8.0 $\mu$m/4.5 $\mu$m, 5.8 $\mu$m/4.5 $\mu$m and 3.6 $\mu$m/4.5 $\mu$m flux ratios over the sources. This was undertaken by estimating the levels of background emission, removing these from the 3.6, 4.5, 5.8 and 8.0 $\mu$m images, and subsequently setting values at $<3\sigma_{\text{rms}}$ noise levels to zero. The maps were then ratioed on a pixel-by-pixel basis, and the results contoured using standard IRAF programs. Contour levels are given through $R_n = A10^{n-16}$, where the parameters ($A, B$) are provided in the captions to the figures.

Some care must be taken in interpreting the flux ratio results, however. The problems with large aperture photometry are described in the IRAC data handbook, and relate in part to scattering in an epoxy layer between the detector and multiplexer (Cohen et al. 2007). This leads to the need for flux corrections as described in table 5.7 of the handbook, corrections which are of maximum order 0.944 at 3.6 $\mu$m, 0.937 at 4.5 $\mu$m, 0.772 at 5.8 $\mu$m and 0.737 at 8.0 $\mu$m. However, the precise value of this correction also depends on the underlying surface brightness distribution of the source, and for objects with size $\sim$ several arcminutes it is counselled to use corrections which are somewhat smaller. The handbook concludes “this remains one of the largest outstanding calibration problems of IRAC”.

We have, in the face of these problems, chosen to leave the flux ratio mapping unchanged. The maximum correction factors for the 8.0 $\mu$m/4.5 $\mu$m and 5.8 $\mu$m/4.5 $\mu$m ratios are likely to be $>0.8$, but less than unity, and ignoring this correction has little effect upon our interpretation of the results.

Finally, we have produced emission and ratio profiles for ring features found within the haloes of these sources. This involves taking slices across the rings, and removing smoother and underlying components of emission. We have also employed a ‘jitter’ procedure first introduced by Corradi et al. (2004), in which a source image is displaced by a certain number of pixels in four orthogonal directions. The original image is then divided by the four displaced images, and the resulting ratio maps combined. This leads to enhancement...
of the ring structures, and effective removal of the underlying halo emission.

The 2MASS was undertaken between 1997 and 2001 using 1.3 m telescopes based at Mt Hopkins, Arizona, and at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. Each telescope was equipped with a three-channel camera, each consisting of a 256 × 256 array of HgCdTe detectors, and this permitted simultaneous observations of the sky in the J (1.25 μm), H (1.65 μm) and Ks (2.17 μm) photometric bands. Details of the data bases employed and procedures used in the analysis of the data can be found in Skrutskie et al. (2006). The 2MASS results for NGC 3242 and NGC 7354 were acquired using the NASA Infrared Science Archive (IRSA), combined into three-band colour imaging, and directly compared with results derived from the HST and SST. We have in this case represented J-band fluxes as blue, H-band fluxes as green and Ks emission as red.

The HST was launched in 1990 April, and consists of an f/24 2.4 m Ritchey–Chrétien reflector. The observations of NGC 7354 were obtained on 2001 July 29 using the WFPC2 (Holtzman et al. 1995), and were acquired as part of program 8773. The fits results were downloaded from the Hubble Legacy Archive at http://hla.stsci.edu/, and processed and combined to yield colour-coded images of the source. In this case, we have selected exposures taken with filter F502N (central wavelength λc = 5013 Å, bandwidth Δλ = 47 Å) corresponding to emission from the λ5007 transition of [O iii], and for which the total exposure time was Δt = 700 s; filter F555W, for which λc = 5410 Å, Δλ = 1605 Å and Δt = 260 s, and which is dominated by the nebular continuum; and filter F658N which for λc = 6858 Å, Δλ = 20 Å and Δt = 989 s, and which corresponds primarily to the λ6584 Å transition of [N ii]. These three filters are represented in our combined image of the source as (respectively) blue, green and red, whilst the spatial resolution is 0.10 arcsec pixel−1.

Finally, the F658N filter is known to leak a certain amount of flux from the adjoining Hα transition. We however note that emission from this filter is concentrated in a patchy circum-nebular waist that bears little resemblance to the visual continuum, or 6 cm radio mapping of the source (see e.g. Fig. 1, and Hjellming, Bignell & Balick 1978; the authors are unaware of any comparative Hα imaging). It is therefore unlikely that contamination by Hα is appreciable, or will seriously affect the apparent distribution of [N ii].

3 OBSERVATIONAL RESULTS

3.1 The case of NGC 7354

3.1.1 The characteristics of nuclear emission

Visual observations of the bright central nucleus of NGC 7354 reveal it to have an ellipsoidal morphology, and to be composed of an inner rim with aspect ratio ∼1.6 and major axis length ≥30 arcsec, and a fainter shell with major axis dimensions ≤33 arcsec and a morphology which is almost circular (aspect ratio ∼1.1). These two components are probably best interpreted in terms of a bubble blown rim/D-type shell structures described in Section 1. The velocity pattern of the rim is consistent with what would be expected for a spheroidal shell, and implies inclination-corrected expansion velocities of 24.5 km s−1 in [O iii] and 27.0 km s−1 for [N ii] (Sabbi, Bianchini & Hamzaoglu 1983).

The Zanstra temperatures summarized by Phillips (2003a) imply mean values of Tz(H i) = 52.5 kK and Tz(He ii) = 98.7 kK. Such disparities in temperature are usually taken to imply that the shell is optically thin to H ionizing radiation, whilst the large value of Tz(He ii) suggests a comparably large stellar effective temperature.

HST imaging of the source is illustrated in Fig. 1, obtained from a combination of HST exposures derived from the Hubble Legacy Archive. We have used results taken in [N ii] (coloured red), continuum (green) and [O iii] (blue) (see Section 2 for details). The corresponding 2MASS and Spitzer IRAC results, by contrast, are illustrated in the upper central and right-hand panels of Fig. 1, and again correspond to the combined results for all of the photometric bands, as described in Section 2. The latter results have also been processed using unsharp imaging techniques, which tends to emphasize finer and fainter aspects of the nebular structure.

The various [N ii] features in the inner shell of NGC 7354, evident in the HST imaging in Fig. 1, are identifiable with the Fast Low-Excitation Regions (FLIERS) analysed in a series of papers by Balick and colleagues (Balick et al. 1993, 1994, 1998; Hajian et al. 1997), structures whose origins remain in doubt, but which have been observed in some 10 or so PNe to date (a couple of these features are labelled in Fig. 1). Whilst the kinematics of the NGC 7354 FLIERS are poorly determined, Hajian et al. (1997) consider that the unusual line emission properties of these structures are more likely to arise from photoionization rather than shocks. Whatever their origins, however, it would seem that at least certain of the FLIERS may be enhanced in the infrared as well, including features in the upper right-hand corner of the interior shell, apparently visible in the NIR (2MASS) and Spitzer (MIR) results. These are located at ∼15 arcsec from the central star, and along a position angle (PA) of 310°. It is also possible that the jet-like extensions, at the major axis limits of the inner rim, may be visible in the Spitzer image of the source. Having said this, however, it should be noted that the relatively poorer resolutions of the 2MASS and Spitzer results may imply that at least certain of these features correspond to unrelated background sources.

A further characteristic of interest in the Spitzer imaging of this source is the red colouration of the halo, outside of the bright (and more elliptical) inner rim. This arises because of enhanced 5.8 and 8.0 μm emission, as discussed in our more detailed analysis below and may indicate the presence of small PAH emitting dust particles, outside of denser portions of the core.

3.1.2 Halo emission in NGC 7354

A larger scaled image of the source is illustrated in Fig. 2, where we have again combined colour-coded IRAC band results, as described above, and processed the results using unsharp masking techniques. It will be seen that the bright central shell is surrounded by a much fainter and circular halo. This halo has a diameter of ∼110 arcsec, contains at least three inner ring structures and may also be surrounded by a much larger and more diffuse shell with diameter ≈250 arcsec. The latter structure is seen very faintly and partially at 5.8 μm, but is at its clearest (and strongest) at 8.0 μm.

This outermost shell may represent unrelated line-of-sight (LOS) emission, or components of the ISM which are being ionized by the PN central star. We would argue, however, that neither of these is likely to be the case. Not only is the emission centred on NGC 7354, and appears roughly circular in appearance, but it also appears to be separated from the interior halo by a circular and lower intensity regime. It may therefore be that this outer shell was emitted during the earliest phases of AGB mass loss, an event which
was followed by a relative lull, and the final superwind phase of evolution.

Profiles through the source are illustrated in Fig. 3, where the several components of envelope emission are again in plain evidence. In this example, and for all of the other profiles to be considered here, the zero point corresponds to the central star position. The directions and widths of the slices are indicated in the figure captions, as are the positions corresponding to negative axial displacement (or relative position – hereafter referred to as RP). The surface brightnesses correspond to an average of pixel values between the limits of the slice, and over a direction which is orthogonal to that of the slice.

Emission in the high intensity central emission plateau, corresponding to the region of the wind-blown rim, falls off steeply at its edges over a distance of ~10 arcsec. This region of surface brightness fall-off arises in the surrounding, more circular shell noted in Fig. 1, and corresponds to material which may have been ionized by a D-type front (see Section 1). There follows, after this, a marked moderation in the fall-off of shell surface brightness, in a region corresponding to the inner portions of the outer halo. The radial exponent β in this region has a value close to ~0. The surface brightness then again falls off steeply in all of the wavebands, as is further illustrated in Fig. 4.

We have, for the latter figure, represented radial trends in surface brightness for the three longest wavelength MIR channels, and for three radial slices starting at the nucleus. The scatter in the results is an indication of the variations in fall-off for the differing radial directions, rather than representing photometric uncertainties in the measured fluxes.

It can be seen from this that although there is a rapid steepening in gradients with distance from the nucleus, one can identify three primary gradients in the decline of the halo surface brightness. At 4.5 μm for instance (and the results are also very similar at 3.6 μm as well), the exponent β varies from ~0 for RPs < 32 arcsec (i.e. log (RP/arcsec) < 1.51), to ~4 for 32 < RP < 50 arcsec and β ~ 12 for RP > 50 arcsec. This last value is certainly very steep, and it could be argued that a simple cut-off in the halo at RP = 50 arcsec, allied to the instrumental response function, might lead to somewhat similar declines in intensity. However, our analysis of PSFs associated with stars within the field suggests that values of β would, in that case, approach something closer to ~20. It therefore follows that although instrumental scattering effects may contribute to this trend, much of the final steep decline is likely to be real. This, should it be confirmed, may testify to an initial rapid increase in dM/dr at the onset of progenitor superwind mass loss.

By contrast, the surface brightnesses at 5.8 and 8.0 μm fall off somewhat less steeply, with β varying from 0 to 3 to 10 within the same ranges of distance from the central star.

It is not entirely clear what emission mechanisms are at work within the halo, although some insight may be gleaned from ratioing the various photometric bands. These ratios are illustrated in Fig. 4, and in the upper three panels of Fig. 5. It is clear, from the former diagram, that nuclear levels of 3.6, 4.5 and 5.8 μm emission are rather similar, and lead to ratios 3.6 μm/4.5 μm and 5.8 μm/4.5 μm which are close to ~0.3 → 0.5.

All of these ratios change markedly as one exits from the nucleus, however. In the first place, it is clear that the 8.0 μm/4.5 μm and 5.8μm/4.5 μm ratios increase rapidly as one passes through the inner bright shell, up to a distance of 24 arcsec from the nucleus. This also occurs, in a more modest way, for the 3.6 μm/4.5 μm ratio as well, although this latter variation is less apparent in Fig. 3. Finally, the rate of change in the ratios moderates greatly at distances >24 arcsec from the nucleus, where they take the typical values 8.0 μm/4.5 μm ~ 6, 5.8 μm/4.5 μm ~ 1.8 and 3.6 μm/4.5 μm ~ 0.9.

This variation in ratios is seen even more clearly in the upper three panels of Fig. 5, where we illustrate ratio variations over the projected surface of the source. One may note here the low ratios associated with the inner rim, the intermediate ratios connected with the inner shell, and the roughly uniform and higher ratios in the outer halo.
Figure 3. The variation of surface brightness through the centre of NGC 7354 (upper panel), where it will be noted that the vertical axis is in logarithmic units. The direction and width of the slice are indicated in the inserted image. The lower panel, by contrast, shows the variation of 8.0 $\mu$m/4.5 $\mu$m, 5.8 $\mu$m/4.5 $\mu$m and 3.6 $\mu$m/4.5 $\mu$m flux ratios close to the central region of the source. It will be noted that the 5.8 $\mu$m/4.5 $\mu$m and 8.0 $\mu$m/4.5 $\mu$m ratios show particularly strong increases towards the halo (i.e. for $|RP| > 14$ arcsec). The slit is oriented in an approximate N–S direction (see the inserted panel) and has a width of 4.7 arcsec. Negative positional offsets correspond to the southern side of the central star (upper right-hand panel of the inserted image).

Apart from this, we note that this halo has not been observed in H$\alpha$ + [N II] down to very low levels – to surface brightnesses which are $< 2 \times 10^{-3}$ of the central source intensity. Corradi et al. (2003), on the basis of this, concluded that the halo in this source likely did not exist at all. However, exist it does, as our present results testify, and at an MIR surface brightness which is, at its brightest, $\sim 0.07$ of that in the central core.

So it is apparent that flux ratios vary markedly with position in the source, and that relative levels of fluxes in the MIR are quite different from those in the visible – the haloes are relatively much more bright. The same pattern of behaviour applies for NGC 3242 as well (see below), and we shall discuss some of the mechanisms which might be responsible for this in Section 3.2.2.
3.1.3 The ring system in NGC 7354

Finally, we have taken a radial slice through the south-east sector of the halo, and fitted the underlying emission with a sixth-order least-squares polynomial fit. This smoother, underlying fall-off is then removed from the total halo emission, leaving the peaks corresponding to the ring components alone. The results are illustrated in Fig. 6 for the four MIR photometric channels. Note here that although the median fall-off in halo surface brightness can be well approximated by a series of power-law trends (see Section 3.1.2), it is clear that this fall-off is subject to small-scale fluctuations which derive from intrinsic variations in the structure of the region. This is responsible for much of the scatter in Fig. 4. It is therefore not particularly useful to apply such laws in removing the underlying (and smoother) components of emission – particularly given that the rings themselves are relatively weak.

An aspect of this analysis which is of particular interest arises from the possibility that particle drift could lead to positional decoupling of the dust and gaseous rings (see Section 1). Where the emission mechanisms of the 3.6 and 8.0 μm ring components differ, such that the 3.6 μm flux is dominated by plasma and line components of emission and that at 8.0 μm arises from small PAH emitting grains, one might then see some relative displacement in the rings in these differing wavelength regimes.

This may, indeed, be what is occurring in the present source – although if this is the case, then the degree of decoupling must be small. The short and longer wavelength rings are in approximate register, and any separation of the peaks is likely to be < 0.25 times the inter-ring spacing. This will also be found to be the case for NGC 3242 (see Section 3.2.3).

Such a result, should it be confirmed, may imply that the dust pattern is not drifting to any appreciable degree compared to its...
Figure 5. Flux ratio maps for NGC 3242 and NGC 7354. It will be noted that both sets of maps are closely similar, and show evidence for much lower ratios within the inner rim-like structures (delineated using darker shades of grey), somewhat higher values for the interior shells, located just outside of the rims and, finally, very much higher ratios for the haloes (where grey levels are also at their lightest). In cases where flux ratios $R_n$ are represented through $R_n = A^{(n-1)}B$, the contour parameters $[A,B]$ in NGC 3242 are given by $[1.3, 0.1384]$ for $3.6 \mu m/4.5 \mu m$, $[0.4, 0.175]$ for $5.8 \mu m/4.5 \mu m$ and $[0.4, 0.0828]$ for $8.0 \mu m/4.5 \mu m$. The corresponding parameters for NGC 7354 are given by $[0.2, 0.0625]$ for $3.6 \mu m/4.5 \mu m$, $[0.35, 0.0756]$ for $5.8 \mu m/4.5 \mu m$ and $[1, 0.0625]$ for $8.0 \mu m/4.5 \mu m$.

3.2 The case of NGC 3242

3.2.1 The characteristics of nuclear emission

NGC 3242 is not exactly a carbon copy of NGC 7354, but it is the next best thing. Suffice to say that it has Zanstra temperatures $T_Z(H \text{I}) \approx 56.3 \text{ kK}$ and $T_Z(\text{He II}) \approx 89.9 \text{ kK}$ which are closely similar (Phillips 2003a; see also the detailed analysis of the central star temperature given by Pottasch & Bernard-Salas 2008); and the kinematic structures of the shell/rim are comparable, and imply somewhat similar velocities of expansion $\sim 20–30 \text{ km s}^{-1}$ (Balick, Preston & Icke 1987; Meaburn, López & Noriega-Crespo 2000). It also has comparable evidence for FLIERS/jets along the major axis of the inner shell, features which have been investigated by Balick et al. (1993) (one of these is labelled in Fig. 1).

The HST, 2MASS and Spitzer images of the source are illustrated in Fig. 1, where the HST image is adapted from a version created by Bruce Balick & colleagues, available at http://www.spacetelescope.org/images/html/opo9738c3.html. In this case, emission in the filters F658N ([N II]), F502N ([O III]) and F469N (HeII $\lambda 4686$ Å) are indicated, respectively, as red, green and blue. We have also created the 2MASS and Spitzer results by processing original J, H, Ks and IRAC MIR images as described in Section 2. Again, note that the 2MASS and Spitzer images correspond to unsharp masked results, designed to reveal finer details of the nebular structures.

Several things may be noted from an inter-comparison of the images. First, the inner bright ring is better resolved (or more sharp)
than was the case for NGC 7354, and also appears to be more complete, but otherwise shows a similar morphology and aspect ratio.

Second, the inner shell about the rim has a major axis dimension of $\sim40$ arcsec, is elliptical, and is apparent in all of the wavebands, from the visual through to the MIR. It has a grey colour in the Spitzer and 2MASS imaging, indicative of reasonably strong emission in all of the bands.

3.2.2 The nature and properties of halo emission

The outer halo of NGC 3242 is faintly visible in the HST results, but very much stronger in the MIR (Fig. 1, lower right-hand panel). One can see the presence in the latter image of the three interior rings, and evidence for disruption of the rings to the upper right-hand and lower left-hand portions of the source - a disruption which...

Figure 6. A slice through the ring system of NGC 7354, where underlying emission has been deleted using a sixth-order least-squares polynomial fit. The peaks therefore represent the excess emission associated with the ring features alone. The top panel indicates this emission in terms of MJy sr$^{-1}$, whilst the lower panel represents the ratio $S(R)/S(R + H)$, where $S(R)$ is the surface brightness of the ring and $S(R + H)$ is the surface brightness of the rings and halo combined. The slit is oriented in an approximate N–S direction, and is located in the southern portion of the halo (see the inserted panel). Its width is 10.2 arcsec.
is associated with the arcs or bubbles of emission noted in the HST image of the source.

The most interesting of the MIR images, however, is probably that shown in Fig. 2, where we see evidence for as many as four rings within the halo of the source. This compares with the five rings observed by Corradi et al. (2004) (albeit two of the latter identifications are only partial).

Finally, it will be noted that the outer left-hand limits of the halo show a fragmentary appearance which will be discussed, along with other evidence, in a later paper concerning structural deformities in haloes (Ramos-Larios & Phillips, 2009).

Profiles and flux ratios through the nebula are illustrated in Fig. 7, and show diagnostics very closely similar to those which were noted for NGC 7354. There are however differences. Note for instance how the 3.6 μm/4.5 μm ratios are similar across the source, and of the order of ~0.6. They are not however constant, as noted in the contour map illustrated in Fig. 5, where it will be seen that the ratio increases gradually from the centre to the outer limits.

It is again apparent that the rim region has the lowest 3.6 μm/4.5 μm, 5.8 μm/4.5 μm and 8.0 μm/4.5 μm flux ratios, that the elliptical shell has intermediate values of these parameters and that the largest ratios occur within the halo, where 5.8 μm and
8.0 μm emission is dominant. There is however, unlike the case of NGC 7354, some evidence for a global increase in flux ratios as one passes to larger radii within the halo.

Finally, we note that the inner portion of the halo has an intensity which is ≤0.15 that of peak values – again much larger than the ratio noted for Hα + [N ii] and [O iii] (Corradi et al. 2003).

It is therefore pertinent to ask why the relative MIR halo intensities are so much greater than those in the visible – a situation which applies to both of the sources investigated here. And why do the 5.8 μm/4.5 μm and 8.0 μm/4.5 μm ratios in particular increase to larger distances from the nebular centre?

Some indication of what might be happening may be determined from a Spitzer spectrum of NGC 3242, taken as part of the Space Infrared Telescope Facility/Infrared Spectrograph (SIRTF/IRS) Calibration Program. The observation was acquired on 2005 December 16 as part of program 1427, used a 3.6 × 57 arcsec2 slit oriented at a PA of 110°.5, and was centred at RA(2000) = 10h24m49.2s, Dec.(2000) = −18°32′23″. These data have not been fully processed, and are not illustrated here. However, it is apparent that various MIR bands and continua are of importance for the central portions of the source. We note, in particular, the presence of a broad continuum within the 5.8 μm photometric band – a component which becomes of increasing importance in the 8.0 μm channel. This is probably the dominant contribution to longer wave MIR IRAC fluxes. The 8.0 μm channel also contains strong transitions of [Ar ii] and [Ar iii] at 6.99 and 8.99 μm, and a possible dust band peaking at 7.48 μm, blended with [Na iii] at λ7.319 μm. This band may be interpretable in terms of a combination of C–C stretching and C–H in-plane bending modes associated with PAH-type particles, an interpretation which gains weight from the presence of a further (and much weaker) band at 5.94 μm, which may derive from corresponding C–O stretching modes (see e.g. Tielens 2005 for a discussion of the properties of these particles).

On the other hand, we note that Smith & McLean (2008) appear not to have detected the 3.3 mm PAH band feature in this source (we are grateful to an anonymous referee for drawing our attention to this reference, and to the existence of the Spitzer spectrum described above). Although these results do not necessarily inform us of what may be happening in the halo, they do suggest that dust band and continuum emission may be important. Where this is the case, then it would also explain certain of the flux ratio variations noted above (and illustrated in Figs 4 and 5).

The longer wave emission in this source appears to have lines peaking at 10.54, 25.2 and 25.8 μm, although there is little if any evidence for dust emission bands.

These results, should their interpretation be accepted, appear to fly in the face of previous abundance measurements for this source, implying as they do a C/O abundance ratio > 1. Pottasch & Bernard-Salas (2008), for instance, determine that C/O < 1 for the nuclear regions of NGC 3242, a result that also agrees with most other independent determinations of this parameter (see e.g. the references cited in Pottasch & Bernard-Salas 2008, and the values cited by Phillips 2003b). This outcome, together with arguments concerning N abundances, is used to suggest a progenitor mass <1.5 M⊙.

It therefore follows that this particular PN may be similar to sources in which emission characteristics imply dual C- and O-rich chemistries, a problem which is still under active consideration (see e.g. Gutenkunst et al. 2008; Perea-Calderón et al. 2009). One possible reason for such joint compositions is that late thermal pulses at the end of the AGB may lead to changes in C/O ratios (Waters et al. 1998), although this is just one of six or so possible explanations for this phenomenon.

The reasons for the excess levels of halo emission at shorter wavelengths (3.6 and 4.5 μm) are less easy to understand. Why should halo/core surface brightness ratios be so high when compared to those observed in the visible? One possible reason may be that the visual images of NGC 3242 include both Hα and [N ii] λ6548 and 6583 transitions. It is clear that emission by [N ii] may represent a very important contribution indeed – not least because of its prevalence in the FLIERS noted in the HST imaging in Fig. 1. This contribution might jump up core/halo intensity ratios by factors of 2 or 3, compared to those expected for Hα emission alone. It is also possible that there are particularly strong transitions within the 4.5 μm band, including lines such as Brγ, the forbidden lines [Ar iv] and [Mg iv] close to 4.53 μm, and the shock or fluoresceingly excited v = 0–S(8) and S(9) lines of H2 at λ4.69 and 5.05 μm. Similar H2 transitions may occur in the 3.6 μm channel as well.

Various PNe also appear to have hot dust within their haloes, likely arising from stochastic heating of very small grains (e.g. Borkowski et al. 1994; Ramos-Larios & Phillips 2005; Phillips & Ramos-Larios 2005, 2006, 2007). This leads to characteristic J − H and H − Ks indices in the NIR, and may be associated with the self-same grains as are responsible for the PAH emission bands. The extension of these grains continua to longer infrared wavelengths might very well enhance 3.6 and 4.5 μm emission, and explain the strong increase in halo/core ratios noted above.

Similar processes are probably operable in the halo of NGC 7354, although it is possible that the halo in this source is neutral – a reason for its lack of detection in Hα. Under these circumstances, it is possible that PAH emission bands are particularly important, as noted in previous analyses of such regimes (see e.g. Phillips & Ramos-Larios 2008a,b; Ramos-Larios & Phillips 2008; Ramos-Larios, Phillips & Cuesta 2008).

Finally, the variation of surface brightness with distance is illustrated in Fig. 8. The tendencies are again similar to those which were noted in NGC 7354, although rather less extreme. The inner portions of the halo are characterized by exponents β ∼ 1.7 at 3.6 and 4.5 μm – and it is precisely in this regime that the rings are located. This then steeps to β ∼ 6.3 for RP ≥ 40 arcsec. Again, and as for NGC 3245, gradients are shallower for the 5.8 and 8.0 μm results, with β in the outer region of the halo taking a value ∼4.5.

We note that gradients for the inner parts of the halo have also been determined in the λλ4959 + 5007 Å transitions of [O iii], where the value for β was found to be 4.5 (Monreal-Ibero et al. 2005). This is clearly much steeper than is found in the MIR, and suggests that we need to be careful in interpreting such fall-offs. This question will be further addressed in Section 4.

It is worth noting that the halo discussed above is also surrounded by a much larger region of emission which may or may not be related to NGC 3242 itself (e.g. Deeming 1966; Bond 1981; Zanin & Weinberger 1997). Some of the arguments relating to this envelope have been rehearsed by Meaburn et al. (2000) and Rosado (1986), whilst more recent INT wide field imaging by Corradi, and GALEX images in the ultraviolet and visible have been made available on the Internet (see the sites http://www.ing.iac.es/PR/science/n3242.jpg and http://photojournal.jpl.nasa.gov/catalog/PIA11968). Two of us will be discussing this region in a later paper (Ramos-Larios & Phillips, in preparation), where we will conclude that the emission is unrelated to the NGC 3242 mass-loss process, and likely represents nearby material which is being ionized by the nebular central star. We shall also suggest that it is directly interacting with the halo about this source.

Finally, and as a general comment, we wish to point out that the similarities between these sources, which include the presence...
of FLIERS, high Zanstra temperatures, rings and comparable core emission morphologies, are also shared by many other sources of their ilk. These similarities have not, to our knowledge, been commented upon before.

Thus for instance, fully half of sources having well-defined ring systems also appear to possess FLIERS, suggesting that the two phenomena may be intimately related. Similarly, it is worth noting that NGC 7354 has a rather modest Galactic latitude ($|b| = 2.3^\circ$), whilst NGC 3242 is located at significantly higher latitudes ($|b| = 32^\circ$). In this respect at least, the two sources are somewhat different. Taken as a whole however, we find that both of these groups of nebulae are characterized by large mean values of $|b|$, of the order of 16.0 ± 3.8 for the 10 FLIER sources of Balick et al. (1993, 1994, 1998) and Hajian et al. (1997), and $|b| = 14.8 ± 4.0$ for the 13 clear and probable ring sources of Corradi et al. (2004). Such high mean Galactic latitudes are usually taken to imply low mean progenitor masses (e.g. Phillips 2001), although some care must be taken not to over-interpret the present results. We note for instance that the FLIERS and rings constitute rather finely chiselled features which may prove difficult to discern at larger distances from the Sun. If the sources are located at smaller distances, then this will tend to increase their mean Galactic latitudes. Similarly, it is worth pointing out that haloes are rather delicate by-products of stellar mass-loss history, and will be more easily destroyed by the ISM at lower heights above the Galactic plane. It is therefore possible that a variety of biases, physical as well as observational, may be determining the high apparent latitudes of these particular samples of sources.

3.2.3 The rings in NGC 3242

We have removed underlying, smoother components of halo emission in NGC 3242 using the techniques described in Section 3.1.3. The results are shown in Fig. 9. We were only capable of rescuing two of the rings from these rather noisy results, however, those located at RPs of −31.4 and −40 arcsec.

The results are fascinating, and show that 8 μm emission is strong in both of the rings – much stronger than is the case in other wavebands – and that ratios $I(R)/I(R + H)$ are in all cases comparable. We conclude from this that the rings in NGC 3242 are likely to have enhanced dust components of emission – a situation which is almost certainly the case at longer wavelengths, where PAH emission is likely to be strong, and may very well also be the case at shorter wavelengths as well, where the strength of the emission may indicate the presence of warm thermal grain continua (see Section 3.1.2).

The position of the 8 μm peak at RP ≈ −40.7 arcsec, when compared to the equivalent shorter wavelength peaks, might, at a stretch, suggest some slight displacement between the rings. Not too much confidence should be placed on this single result alone, however. A rather clearer understanding of what may be happening may be gained from Fig. 10, where we have removed the underlying continuum using the procedures of Corradi et al. (2004). This involves producing four versions of an image shifted three pixels to the left and right, up and down. The original unshifted image is then ratioed separately with the four shifted images, and the resulting maps are summed together. It is these mean ratio maps which are illustrated in Fig. 10 together with comparable [O ii] results taken from Corradi et al. (2004).

We have superimposed the narrow white arcs of Corradi et al. (2004), used to define the positions of peak emission in the [O ii] rings, on all three sets of exposures in the visible and MIR. It will be seen that there is no clear displacement between the results – the MIR rings are closely similar in position to those noted in the visible, although the outer partial ring of Corradi et al. (2004) appears to be undetected in the MIR. Given that this is the case, this therefore suggests that the gaseous density enhancements, responsible for the ring features in the visible, are closely co-spatial with the particle density enhancements which we suppose to be responsible for the MIR results.

4 THE RADIAL VARIATION IN SURFACE BRIGHTNESS IN NGC 3242 AND NGC 7354

We have noted that the haloes for NGC 7354 and NGC 3242 have qualitatively similar fall-offs in intensity, which can be characterized through the use of two or three values of the radial exponent β. The inner regions of the sources have values 1.7 < β < 3, for instance, and similar values have also been noted for NGC 650 (Ueta 2006; Ramos-Larios et al. 2008) and in the visible (see above). These exponents β subsequently increase to values which are very much larger, in the region of 4.5 < β < 10. The former gradients are similar to what would be expected from hydrodynamic modelling of AGB mass loss, and the resulting decrement in electron densities (see e.g. Schönberner & Steffen 2002; Steffen & Schönberner 2003; Schönberner et al. 2005; Sandin et al. 2008).

We have also noted that the value of β differs between the shorter and longer wave results, and with respect to at least one measure of β acquired in the $\lambda\lambda$4959 + 5007 Å transitions of [O ii]. Thus, (Monreal-Ibero et al. 2005) find $\beta \equiv 4.5$ for the variation of [O ii]
Rings and haloes in the mid-infrared

Figure 9. Emission for two of the rings in NGC 3242, where details are otherwise as stated in Fig. 6. The slit is oriented in an approximate E–W direction, and is located in the eastern portion of the halo (see the inserted panel). Its width is 6.7 arcsec.

intensity within the inner halo of NGC 3242, whilst the 3.6 and 4.5 μm fall-offs are better represented by β ≃ 1.7.

So there arises the interesting question of what these results might imply in terms of the variation in halo physical properties. The [O III] and Hα + [N II] fall-offs measured by Corradi et al. (2004), Monreal-Ibero et al. (2005) and Schönberner et al. (2005), for instance, indicate that 3.3 < β < 4.5 for a variety of PNe. These may be directly dependent upon the variation of $n_e^2$ through the nebular shells, appropriately integrated along the LOS, and/or may be influenced by ionization stratification in the outer reaches of the sources. It is interesting, in this context, to note that Sandin et al. (2008) determine $2 < \alpha < 8$ where $n_e \propto r^{-\alpha}$.

Similar doubts arise for the present MIR results. The fall-off at longer wavelengths, for instance, may be influenced by variations in grain number densities, in the grain size distribution $n(a)$, and in decreasing levels of photon extinction at larger distances from the central star. The 3.6 and 4.5 μm results, by contrast, may depend upon the presence of a variety of forbidden and permitted line transitions (see e.g. Section 3.1.2), 3.3 μm PAH emission, warm grain continua and thermal bremsstrahlung emission.

So the situation, taken all in all, appears to be rather unclear. We shall consider below how such variations in surface brightness compare with those expected from mass-loss modelling of a C-rich progenitor, and where one assumes that halo emission derives from either grain bands and/or continua, or an ionized halo.

The progenitor star is assumed to have a representative mass of $2.25 M_\odot$, a value which falls at the lower end of the range expected for C-rich, solar metallicity AGB models (see e.g. Wachter...
et al. 2002; Marigo 2008). Where masses are somewhat less than this (say <1.5 M⊙), then third dredge-up is unlikely to occur, and carbon abundances remain relatively low. Where masses are >4 → 5 M⊙, on the other hand, then hot bottom CNO burning causes C surface abundances to decline (e.g. Herwig & Blocker 2000). Detailed analyses of these and other mechanisms can be found in Busso, Gallino & Wasserburg (1999) and Lattanzio & Wood (2004).

We have chosen the range of C-rich AGB progenitors because radiatively driven mass loss appears to be more efficient in such stars: the mean Planck pressure coefficients for amorphous carbon grains, for instance, are approximately five times as great as those for silicates, a disparity which requires significantly higher luminosities to produce O-rich stellar winds (Woitke 2006) – luminosities such as are found in massive hot-bottom burning O-rich AGB giants.

The naive assumption of a constant outflow with a constant mass-loss rate yields a density profile r−2. Considering that the final, dust-driven ‘superwind’ increases until shortly before its end (see e.g. the models of Schröder, Winters & Sedlmayr 1999), a steeper density profile is generally to be expected for the outer envelopes of PNe.

Hence, the question arises: can a plateau, followed by a much steeper density decline – such as suggested by the present observations of NGC 7354, with the case of NGC 3242 not being too much different – be explained naturally by the superwind-mass-loss history alone, or do we need more exotic physics to explain this?

In order to investigate this question, we here used mass-loss histories derived from a well-calibrated and tested fast evolution code (Pols et al. 1997, 1998; Schröder, Pols & Eggleton 1997), originally developed by Peter Eggleton at the IoA Cambridge (Eggleton 1971, 1972, 1973), which we have combined with the parametrized mass-loss rates of detailed models of dust-driven, C-rich winds by the Sedlmayr group in Berlin (see Schröder et al. 1999 and references therein). These dynamical wind models, which required massive CPU time on a Cray super-computer, include microscopic dust-formation chemistry (PAH-related), radiative transport (all time-dependent) and a periodic piston at the inner boundary to simulate the mechanical energy input for the extended giant chromosphere, below the dust-formation region.

From the time-averaged mass-loss rates of 50 models with different basic physical parameters of the supergiant (L, M, T eff), a parametrized mass-loss description was then derived (Wachter et al. 2002).

This was employed by our evolution code at each time-step. The macroscopic, mutual feedback between the changing physical properties of the supergiant and the mass-loss rate is what shapes the resulting mass-loss histories. A steep rise in the superwind mass loss in the final 20–30 000 yr results, whilst the right order of magnitude of peak mass-loss rate arises as an enforced consequence of the analysis (see Fig. 11), without the need for ad-hoc parameters.

The dust-formation chemistry of O-rich winds [among the more massive thermally pulsing AGB (TP-AGB) supergiants] is much more complicated, and quantitative wind models are still difficult to compute. But there is good reason to assume that O-rich chemistry leads to very similar mass-loss histories, since there is a similarly strong dependence of the mass-loss rate on the basic stellar parameters, and the comparable magnitude of the mass loss ensures a similar influence on the physical properties of the TP-AGB supergiant.

To derive the resulting density profiles, we start with the simplest of possible assumptions as follows.

(i) A constant outflow velocity.
(ii) No interaction with the surrounding ISM.
(iii) No alteration of the density profile by the central star radiation fields or winds.
Hence we ignore all possible complex hydrodynamic processes and look only at the expansion of the dust-driven mass loss by the simple equation of continuity. And there are good reasons for such a naive approach: the expansion velocity of a dust-driven wind does not vary quickly and vastly with time, and the outer parts of many PNe appear undisturbed by the fundamental changes in their centres. At the same time, their density is sufficiently larger than that of the surrounding ISM to suggest that any interaction with the latter only leads to secondary effects on the density profile.

A look at a typical mass-loss history (see Fig. 11) immediately suggests that a plateau-like density distribution could arise from the falling post-peak mass loss, while the steeply increasing pre-peak superwind mass loss should produce a very steep, outer density profile – just as observed for NGC 7354 (Fig. 4). We have assumed here a distance of 1.19 kpc based upon the statistical result of Phillips (2004) (a very similar distance is also obtained by Zhang 1995), whence the innermost result; at 25 arcsec (1.4 dex) from the centre, corresponds to a physical radius of 4.46 × 10^17 cm (log r_1 = 17.65), and the outermost (63 arcsec or 1.8 dex) to 1.12 × 10^18 cm (log r_2 = 18.05). We have also assumed an expansion velocity of 26 km s^{-1} based on a mean of the [O ii] and [N ii] results of Sabbadin et al. (1983), a value which likely corresponds to a severe upper limit for the halo expansion itself. Given such a value, the radial range in Fig. 12 would correspond to a mass-loss history of 8200 yr. About 2/3 of this history is pre-peak and 1/3 is post-peak. During this episode alone, our TP-AGB supergiant model (Fig. 11), with M_i = 2.25 M_⊙, loses 0.4 M_⊙ to the halo wind. If we dilute that into the above radial range (see Fig. 12), then densities drop to o(10^{-22}) g cm^{-3}.

Where 4.5 μm emission is predominantly produced by optically thin, collisionally excited recombination, rather than by scattered light or grain thermal emission (although see our previous comments in Section 3.1.2), then every volume element contributes a flux proportional to the local density squared, and the observed flux at any radial point is simply the LOS integral over n_2. This steepens the radial flux profile when compared to the radial density profile. Thus, where the model density fall-off is as noted in the upper left-hand panel of Fig. 12, then one obtains the LOS-n_2 profile illustrated in the upper right-hand panel of this figure. This exhibits a nearly plateau-like inner part and a steep ∼ r^{-1} to r^{-3} outer part, a result which bears a striking similarity with our observations in Fig. 4. The shell of NGC 3242 is a similar, but more compact, younger case: if we adopt a distance of 0.5 kpc, similar to the expansion distances of Terzian (1997) and Jacoby (1980) (see also Pottasch 1996; Mellema 2004), then the inner observed point at 18 arcsec (1.25 dex) corresponds to a physical radius of 1.35 × 10^17 cm (log r_1 = 17.125), and the outer (70 arcsec, 1.85 dex) to 5.3 × 10^17 cm (log r_2 = 17.725). Similarly, where one assumes an outflow velocity of 27 km s^{-1}, similar to the mean of [N ii] and [O ii] velocities for the nucleus of the source (Balick et al. 1987; Weinberger 1989)—values which are again likely to constitute upper limits for the halo expansion velocity—then the observed flux profile can be understood in terms of the same mass-loss history as for NGC 7354, but for an earlier phase of expansion (see the lower left-hand panel of Fig. 12). The lower right-hand panel of Fig. 12 shows the resulting LOS-n_2 profile (again the radius is given in arcsec), a result which is qualitatively similar to the observed profile for NGC 3242 (see Fig. 8). Although the correspondence is not precise—there is no 'break', or rapid change in model fall-off gradients such as appear to be indicated in the observations, for instance—there is a significant change in β, from values ∼ −1.4 at smaller radial distances (log(r/arcsec) < 1.55) to ∼ −1.8 at larger distances. On the other hand, where one adopts a slower outflow velocity for the outer haloes than the 26 → 27 km s^{-1} used here, then the pattern scale of the projected mass-loss history would be reduced, and we would see an even steeper decline in the PNe outer haloes—a result which is closer to the observational results noted above.

With the encouraging similarities found above, we may conclude that the observed density profiles are reasonably consistent with the superwind mass-loss history, and that in a first approximation, no complicated hydrodynamical effects are needed to understand these trends.

The present LOS-n_2 results are valid for ionized nebular outflows, and may be appropriate for the 3.6 and 4.5 μm results depending upon what the predominant emission mechanisms might be. Given this situation, it would be interesting to marry the present analysis to hydrodynamic modelling of fully ionized haloes. However, we note that where halo temperatures are uniform (although see our comments in Section 1), and ionization of the exterior haloes occurs over a time-scale of ∼10^7 yr (see Section 1), then it is likely that the structures would be homologously related to their non-ionized counterparts: whilst expansion velocities and size scales would be larger, the nature of the density fall-offs would be comparable.

Where dust emission is dominant at 5.8 and 8.0 μm (although this has yet to be proven), then the models would imply an exponent β of the order of ∼0 at smaller radii, increasing to ∼3.3 at larger radii—assuming that the number density of dust grains is proportional to the gas density; that the variation n(a) in the number density of dust grains with grain radius a is invariant with r; and where excitation processes are invariant with distance from the nucleus. This represents a somewhat unlikely suite of properties. Nevertheless, it is clear that the fall-off in emission would be somewhat less than that determined where line and continuum emission processes dominate fluxes.

5 CONCLUSIONS
We have presented imaging of the PNe NGC 7354 and NGC 3242 in four MIR photometric bands, acquired through program P30285 undertaken with the SST.

NGC 7354 has been shown, for the first time, to have a halo of diameter ∼110 arcsec (and possibly larger), whilst the halo in

Figure 11. Final mass-loss history for an initial stellar mass of M_i = 2.25 M_⊙, solar composition and C-rich dust-formation chemistry. Marks indicate the decreasing, actual mass of the TP-AGB supergiant. Both short- and long-term variations of the mass-loss rate are caused by thermal pulses.
NGC 3242 has a comparable appearance to that detected in the visible. The level of MIR emission in the haloes, however, compared to those derived from the nebular cores, appears to be an order of magnitude greater than is determined from permitted and forbidden line transitions. The reasons why this should be the case at shorter IRAC wavelengths (3.6 and 4.5 μm) are far from being clear, although it is plain that a mix of differing MIR transitions are capable of helping, including possible contributions from H2, various ionic and forbidden lines, and the 3.3 PAH band and associated plateau component. It has also been suggested that very small grains, such as those responsible for the PAH bands, may also lead to warm NIR continua in the haloes of a variety of other PNe. The extension of these continua to the MIR may explain some of the increase in halo fluxes noted here.

Flux ratios among the 3.6, 5.8 and 8.0 μm bands on the one hand, and the 4.5 μm band on the other, show increases by factors of up to ~5.5 on passing from the nebular nuclei through to the haloes. This sharp increase in ratios may be attributable to the increasing role of PAH band transitions, to the wings of amorphous silicate features peaking at 9.7 μm, to broader warm dust continua and/or to H2 molecular transitions.

The fall-off of surface brightness with radius is dependent upon the IRAC band which is being considered. It is generally less steep at 5.8 and 8.0 μm, and implies radial exponents \( \beta \) ranging from 0 to ~3 in the inner parts of the haloes, where various emission rings are located, to \( \beta \approx 4.5 \rightarrow 10 \) at larger radii. These values increase to 1.7 \( \rightarrow 4 \) and ~6.3 \( \rightarrow 12 \) in the 3.6 and 4.5 μm bands. It is clear, in at least one case (NGC 3242), that the fall-off in the inner halo is much less steep than has been determined in [O iii].

Although the mechanisms responsible for the MIR emission are somewhat uncertain, it is nevertheless evident that MIR gradients in the inner parts of the halo are in accord with those determined in the visible.

We have finally investigated the formation of such haloes by AGB progenitors in which dust formation occurs in C-rich environments, although we also note that similar results are likely to apply where the progenitors are O-rich as well. The resulting fall-off in halo densities, as determined for a series of simplifying (but reasonable) assumptions, is used to determine integrated LOS variations in \( n_e \).

The latter profiles are perhaps most comparable with the surface brightness gradients observed for visual permitted and forbidden line transitions, since the nature of the emission mechanisms in the MIR remains somewhat uncertain. Nevertheless, we find that the model results for NGC 3242 and NGC 7534 are comparable to those observed in the MIR, and more generally, appear similar to visual surface-brightness fall-offs in other PNe as well. The LOS variations in density \( n \), by contrast, are perhaps more relevant where emission derives from dust grains – grains such as may be important in determining fluxes within the 5.8 and 8.0 μm channels. For this...
case, the exponents $\beta$ appear less, as is observed to be the case in our present results.

Apart from the global features of halo emission noted above, we also note that the inner halo of NGC 7354 contains three relatively narrowly defined rings. This is the first time that such rings have been discovered outside of the visual wavelength regime. The mechanisms responsible for halo emission are by no means clear, as noted above, and it is possible that shorter MIR wavelengths are dominated by warm grain continua. It is therefore possible that we are witnessing evidence, in these rings, for radially symmetric enhancements in particle density. This uncertainty apart, however, we note that the innermost ring appears to be particularly enhanced at 8.0 $\mu$m, and this likely testifies to higher concentrations of outflowing grains.

By contrast, the rings in NGC 3242 have been previously observed by Corradi et al. (2004) in H$\alpha$ + [N II], although they again show evidence for enhanced dust emission in at least two of the structures.

Comparison of the positioning of these rings, with respect to both those observed at other MIR wavelengths and (for NGC 3242) those observed in the visible, suggests that they are all closely co-spatial. It is therefore clear that there is little slippage of the ring patterns, and that enhancements in gas density are probably co-spatial with those in particle number densities.

ACKNOWLEDGMENTS

We thank an anonymous referee for his careful review of this work, and several valuable suggestions. This research is based, in part, on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by an award issued by JPL/Caltech. In addition to this, the work makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/Calfornia Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. The 2MASS data was acquired using the NASA/IPAC IRSA, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Finally, various of the results for NGC 3242 were provided by an award issued by JPL/Caltech. In addition to this, the research makes use of data products from the Two Micron All Sky Survey, which is a project of the University of Massachusetts and the Infrared Processing and Analysis Center/Calfornia Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. The 2MASS data was acquired using the NASA/IPAC IRSA, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Finally, various of the results for NGC 3242 were provided by an award issued by JPL/Caltech.

REFERENCES

Balick B., Preston H. L., Icke V., 1987, AJ, 94, 1641
Balick B., Gonzalez G., Frank A., 1992, ApJ, 392, 582
Balick B., Rugers M., Terzian Y., Chengalur J. N., 1993, ApJ, 411, 778
Balick B., Perinotto M., Maccioni A., Terzian Y., Hajian A., 1994, ApJ, 424, 800
Balick B., Alexander J., Hajian A. R., Terzian Y., Perinotto M., Patriarchi P., 1998, AJ, 116, 360
Balick B., Wilson J., Hajian A. R., 2001, AJ, 121, 354
Bond H. E., 1981, PASP, 93, 429
Borkowski K. J., Harrington J. P., Blair W., Bregman J. D., 1994, ApJ, 435, 722
Bryce M., Meaburn J., Walsh J. R., Clegg R. E. S., 1992, MNRAS, 254, 477
Busso M., Gallino R., Wasserburg G. J., 1999, ARA&A, 37, 239
Cohen M. et al., 2007b, ApJ, 660, 343
Corradi R. L. M., Schönberger D., Steffen M., Perinotto M., 2003a, A&A, 354, 1071
Corradi R. L. M., Schönberger D., Steffen M., Perinotto M., 2003b, MNRAS, 340, 417
Corradi R. L. M., Sánchez-Blázquez P., Mellema G., Giammanco C., Schwarz H. E., 2004, A&A, 417, 637
Deeming T. J., 1966, ApJ, 146, 287
Dgani R., Soker N., 1998, ApJ, 495, 337
Eggleton P. P., 1971, MNRAS, 151, 351
Eggleton P. P., 1972, MNRAS, 156, 361
Eggleton P. P., 1973, MNRAS, 163, 179
Fazio G. et al., 2004, ApJS, 154, 10
Garcia-Segura G., Lopez J. A., Franco J., 2001, ApJ, 560, 928
Gutenkunst S., Bernard-Salas J., Pottasch S. R., Sloan G. C., Houck J. R., 2008, ApJ, 680, 1206
Hajian A. R., Balick B., Terzian Y., Perinotto M., 1997, ApJ, 487, 304
Harpsøe A., Rappaport S., Soker N., 1997, ApJ, 487, 809
Herwig F., Blocker T., 2000, in Noels, A., Magain, P., Caro, D., Jehin, E., Parmentier G., Thoul, A., eds, Proc. 35th Liege International Astrophysics Colloquium, The Galactic Halo: From Globular Cluster to Field Stars. Institut d’Astrophysique et de Geophysique, Liege, Belgium, p. 59
Hjelmig R. M., Bignell R. C., Balick B., 1978, Space Telescope, 56, 199
Holtzman J. A., Burrows C. J., Casertano S., Hester J. J., Trauger T. J., Watson A. M., Worthey G., 1995, PASP, 107, 156
Hora J. L., Latter W. B., Allen E. M., Marengo M., Deutsch L. K., Pipper J. J., 2004, ApJS, 154, 296
Hrivnak B. J., Kwok S., Su K. Y. L., 2001, AJ, 121, 2775
Hsia C. H., Ip W.-H., 2007, preprint (arXiv:0712.2639H)
Hyung S., Mellema G., Lee S.-J., Kim H., 2001, A&A, 378, 587
Icke V., Frank A., Henske A., 1992, A&A, 258, 341
Jacoby G. H., 1980, ApJS, 42, 1
Kastner J. H., Montez R. Jr., Balick B., De Marco O., 2008, ApJ, 672, 957
Kwok S., Su K. Y. L., 1998, ApJ, 501, L117
Kwok S., Su K. Y. L., Stoesz J., 2001, in Szczepanek, R., Górny, S. K. ed., Ap&SS Science Library Vol. 265, Post-AGB Objects as a Phase of Stellar Evolution. Kluwer Academic Publishers, Dordrecht, p. 115
Lattanzio J. C., Wood P. R., 2004, in Habing H. J., Olofsson H., eds, Asymptotic Giant Branch Stars. A&A Library, Springer, New York, p. 23
Levi L., 1974, Computer Graph. Image Process., 3, 163
Marigo P., 2008, Mem. Soc. Astron. Ital., 79, 403
Marten H., 1993, A&A, 277, L9
Mastrodemos N., Morris M., 1999, ApJ, 523, 357
Mauron N., Huggins P. J., 1974, Computer Graph. Image Process., 3, 163
Meaburn J., Lopéz J. A., Noriega-Crespo A., 2000, ApJS, 128, 321
Meijerink R., Mellema G., Simis Y., 2003, A&A, 405, 1075
Mellema G., 1994, A&A, 290, 915
Mellema G., 2004, A&A, 416, 623
Monreal-Ibero A., Roth M. M., Schönberger D., Steffen M., Bohm P., 2005, ApJ, 628, L139
Perea-Calderón J. V., García-Hernández D. A., García-Lario P., Szczepanek R., Bobrowsky M., 2009, A&A, 495, 5
Perinotto M., Schönberger D., Steffen M., Calonaci C., 2004, A&A, 414, 993
Phillips J. P., 2000, AJ, 119, 2332
Phillips J. P., 2001, PASP, 113, 839
Phillips J. P., 2003a, MNRAS, 344, 501
Phillips J. P., 2003b, MNRAS, 340, 883
Phillips J. P., 2004, MNRAS, 353, 589
Phillips J. P., Ramos-Larios G., 2005, MNRAS, 364, 849
Phillips J. P., Ramos-Larios G., 2006, MNRAS, 368, 1773

© 2009 The Authors. Journal compilation © 2009 RAS, MNRAS 399, 1126–1144

Rings and haloes in the mid-infrared 1143

Downloaded from http://mnras.oxfordjournals.org/ on January 30, 2013
Phillips J. P., Ramos-Larios G., 2007, AJ, 133, 847
Phillips J. P., Ramos-Larios G., 2008a, MNRAS, 383, 1029
Phillips J. P., Ramos-Larios G., 2008b, MNRAS, 386, 995
Pols O. R., Tout C. A., Schröder K.-P., Eggleton P. P., Manners J., 1997, MNRAS, 289, 869
Pols O. R., Schröder K.-P., Hurley J. R., Tout C. A., Eggleton P. P., 1998, MNRAS, 298, 525
Pottasch S. R., 1996, A&A, 307, 561
Pottasch S. R., Bernard-Salas J., 2008, A&A, 490, 715
Ramos-Larios G., Phillips J. P., 2005, MNRAS, 357, 732
Ramos-Larios G., Phillips J. P., 2008, MNRAS, 390, 1014
Ramos-Larios G., Phillips J. P., 2009, MNRAS, in press
Ramos-Larios G., Guerrero M., Miranda L. F., 2008a, AJ, 135, 1441
Ramos-Larios G., Phillips J. P., Cuesta L., 2008b, MNRAS, 391, 52
Rosado M., 1986, Rev. Mex. Astron. Astrofis., 13, 49
Sabbadin F., Bianchini A., Hamzaoglu E., 1993, A&A, 310, 603
Sahai R. et al., 1998, ApJ, 493, 301
Sandin C., Schönberner D., Roth M. M., Steffen M., Böhm P., Monreal-Ibero A., 2008, A&A, 486, 545
Schönberner D., Steffen M., 2002, Rev. Mex. Astron. Astrofis. (Serie de Conferencias), 12, 144
Schönberner D., Jacob R., Steffen M., Perinotto M., Corradi R. L., Acker A., 2005, A&A, 431, 963
Schröder K.-P., Pols O. R., Eggleton P. P., 1997, MNRAS, 285, 696
Schröder K.-P., Winters J. M., Sedlmayr E., 1999, A&A, 349, 898
Simis Y. J. W., Icke V., Dominik C., 2001, A&A, 371, 205
Skrutskie M. F. et al., 2006, AJ, 131, 1163
Smith E. C. D., McLean I. S., 2008, ApJ, 676, 408
Soker N., 2000, ApJ, 540, 436
Soker N., Zucker D. B., 1997, MNRAS, 289, 665
Steffen M., Schönberner D., 2003, in Kwok S., Dopita M., Sutherland R., eds. Proc. IAU Symp. 201, Planetary Nebulae: Their Evolution and Role in the Universe, Astron. Soc. Pac., San Francisco, p. 439
Su K. Y. L., Volk K., Kwok S., Hrivnak B. J., 1998, ApJ, 508, 744
Terzian Y., 1997, in Habing H. J., Lamers H. J. G. L. M., eds. Proc. IAU Symp. 180, Planetary nebulae. Kluwer Academic Publishers, Holland, p. 29
Terzian Y., Hajian A. R., 2000, in Kastner J. H., Soker N., Rappaport S., eds. ASP Conf. Ser. Vol. 199, Asymmetrical Planetary Nebulae II: From Origins to Microstructures. Astron. Soc. Pac., San Francisco, p. 33
Tielens A. G. M., 2005, The Physics and Chemistry of the Interstellar Medium, Cambridge Univ. Press, Cambridge
Tweed R. W., Kwitter K. B., 1994, AJ, 108, 188
Tweed R. W., Kwitter K. B., 1996, ApJS, 107, 255
Tylenza R., 1986, A&A, 156, 217
Ueta T., 2006, ApJ, 650, 228
Van Horn H. M., Thomas J. H., Frank A., Blackman E. G., 2003, ApJ, 585, 983
Villaver E., Manchado A., García-Segura G., 2000, Rev. Mex. Astron. Astrofis., 9, 213
Wachter A., Schröder K.-P., Winters J.-M., Arnlt T., Sedlmayr E., 2002, A&A, 384, 452
Waters L. B. F. M., Beintema D. A., Zijlstra A. A. et al., 1998, A&A, 331, L61
Weinberger R., 1989, A&AS, 78, 301
Woitek P., 2006, A&A, 460, 9
Xilouris K. M., Papamastorakis J., Paleologou E., Terzian Y., 1996, A&A, 310, 603
Yu Y. S., Nasdew R., Kastner J. H., Houck J., Behar E., Soker N., 2009, ApJ, 690, 440
Zanin C., Weinberger R., 1997, in Habing H. J., Lamers H. J. G. L. M., eds. Proc. IAU Symp. 180, Planetary Nebulae. Kluwer Academic Publishers, Holland, p. 290
Zhang C. Y., 1995, ApJS, 98, 659
Zijlstra A. A., Bedding T. R., Mattei J. A., 2002, MNRAS, 334, 498

This paper has been typeset from a MS Word file prepared by the author.