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# On the spectroscopic detection of faint haloes and reflection nebulae around planetary nebulae

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**Summary.** Attention is drawn to problems involved in the detection of low surface-brightness haloes around bright planetary nebulae and similar objects. These include the far-field scattering or seeing profile and the faint diffuse galactic background. We illustrate the former effect with new observations of compact planetaries and published surface-brightness profiles. The scattering efficiency is found to rise sharply below 4000 Å at La Palma, from observations around BD + 30°3069. This is interpreted as due to telescopic and atmospheric effects. Results for model reflection nebulae are compared with observations of scattered light around two planetaries. The reflection around NGC 7027 appears to be real.

## 1 Introduction

There is a 'missing mass' problem for planetary nebulae (PNe): many systems contain $\sim 0.1$ $M_\odot$ of ionized gas, which with a central star of 0.6 $M_\odot$, gives a total of only $\sim 0.7$ $M_\odot$. However, the average initial mass of disc stars which are ending their lives now should be about 1.5 $M_\odot$. The 'deficit' of up to 0.8 $M_\odot$ was probably lost by the progenitor red giant star, and may now be in the form of (i) an ionized, faint giant halo, (ii) a neutral atomic shell or (iii) a molecular shell. Diagnostics for (ii) and (iii) include CO mm-wave lines, $H_2$ infrared emission, absorption by H I (21 cm), Na I or Ca II, excess emission in the 100–800 $\mu$m range from cold dust and scattered Na I D lines (Dinerstein & Sneden 1988). We introduce here a quantitative discussion of a further diagnostic: reflection nebulae.

PN haloes were first reported many years ago (e.g. Millikan 1974; Kaler 1974). Faint ionized ones can be massive: a halo with an electron density of 1 per cent that of the bright 'core' but with a radius eight times larger can have a surface brightness $\sim 3000$ times lower than the core, yet contain five times as much mass. In this note we show that, in the detection of such haloes

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by purely *spectroscopic* means, allowance must be made for scattering by the telescope and atmosphere (King 1971), and for the diffuse galactic background emission studied by Reynolds and collaborators (e.g. Reynolds 1985a, 1988). Some faint halo detections were for example reported by Jewitt, Danielson & Kupferman (1986), Clegg *et al.* (1987), Baessgen, Cerrato & Grewing (1987) and Weller & Heathcote (1987).

For cases (ii) and (iii), the neutral shell will contain dust, and a reflection nebula should surround the planetary. We report a new search for such emission from the favourable candidate nebula, BD + 30°3639, together with new models of reflection nebulae around PNe. Atherton *et al.* (1979) reported detection of such reflection around the bright planetary NGC 7027, which we analyse quantitatively.

## 2 Observational data

Spectra were obtained for the compact planetary BD + 30°3069 on 1987 July 3 and 1988 April 2, and for NGC 7027 on 1988 August 23 and 26, on the Isaac Newton Telescope at La Palma. We used the IDS spectrograph with an IPCS detector on the 235-mm camera and a GEC CCD on the 500-mm camera. The 1988 April data were kindly taken by Dr J. Fordham, with an IPCS MkII detector (Fordham, Bone & Jorden 1986). Long-slit (2-D) spectra were taken both on the central nebulae and with the slit offset by 10–40 arcsec. Saturation problems were avoided by use of neutral density filters (ND 2.0–3.0 dex) on the bright 'cores'. The offset direction was always perpendicular to the slit. Dust was present in the atmosphere, especially during the two summer observing runs. The extinction in Johnson $V$ at the zenith was 0.227, ~ 0.15, 0.177 and 0.277 mag/airmass, respectively, for each date above. Flux calibration was made from wide-slit observations of spectrophotometric standards (Oke 1974). The bright stars Tau Cyg, Ho Peg and HD 050387 were observed with the same setup and the same offsets as the nebulae, to measure the light scattered by the atmosphere, telescope and spectrograph. The data were reduced with the FIGARO package, written by K. Shortridge (see Bridger 1987), on the UCL STARLINK node.

## 3 Results – scattering and reflection nebulae

### 3.1 BD + 30°3639

King (1971) described the far-field 'seeing' (scattering) profile of a star and found an inner, Gaussian-shaped profile plus an outer part of slope $r^{-2}$ called the aureole. His work was confirmed by Kormendy (1973). King ascribed the aureole to scattering in the atmosphere and by the telescope. Our standard star observations are consistent with the King profile, except that the inner portion varied slightly from star to star, presumably due to variations in the seeing. The measured shape of the aureole was the same for all our standard stars to within 30 per cent. Piccirillo (1973) found that large changes in the aureole's level could arise from a variable amount of dirt on telescope mirrors.

For extended sources, the King profile was convolved with an approximation to the surface brightness of the 'core', taken either as a uniform disc or, in some cases, a limb-brightened ring. The convolution program was written by Dr D. J. Monk at UCL. The convolution broadens the scattered profile, as shown in Fig. 1 where we plot the observed H$\alpha$ fluxes around BD + 30°3639 versus radial offset, together with the expected scattering profiles for a point and extended source. Note that in this paper no observations have been corrected for interstellar extinction.

BD + 30°3639 is a compact nebula of radius 3.5 arcsec (Basart & Daub 1987; Bentley *et al.* 1984). For it we adopt the parameters: absolute H$\beta$ flux $F(\mathrm{H}\beta) = 8.7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$

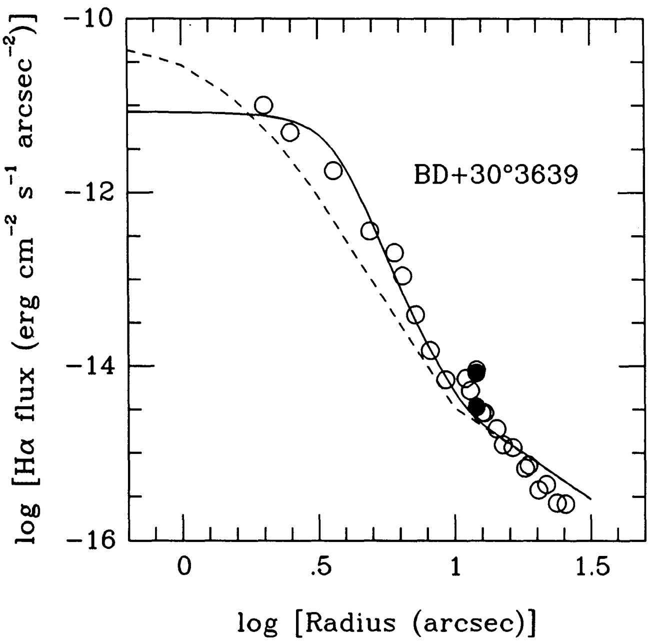

**Figure 1.** Surface brightness of H$\alpha$ versus radius, around BD + 30°3069 (of nominal radius 3.5 arcsec). Open and filled circles denote 1987 and 1988 offset observations, respectively. The dashed and solid lines show the expected King profiles for a point source and for a uniform disc of diameter 7.0 arcsec, respectively. The total observed H$\alpha$ flux is $3.3\times10^{-10}$ erg cm$^{-2}$ s$^{-1}$.

(Persson & Frogel 1973), an electron density of $10^4$ cm$^{-3}$ (Torres-Peimbert & Peimbert 1977) and a reddening constant $c = 0.4$. The total ionized mass is then only 0.024 $M_\odot$ (for an adopted distance of 1.1 kpc, Cudworth 1974). With a central star assumed to have 0.6 $M_\odot$, the total system mass is only 0.62 $M_\odot$. It is so bright that it is one of the best candidates for detection of a reflection nebula; Dinerstein & Sneden (1988) found evidence for a neutral shell from Na I D line emission scattered by circumnebular sodium atoms. But as shown in Fig. 1, our observed offset emission in H$\alpha$ is consistent with scattered light and we therefore cannot interpret the H$\alpha$ data as being significantly due to reflection nebulosity.

There is little information on the colour dependence of the scattering described by King (1971). Pierce (1954) measured this dependence for scattered light close to the Sun's limb in hazy sky conditions at Mount Wilson. We have measured it at La Palma by ratioing the BD + 30°3639 offset spectra to the 'core' spectra. This was done for nebular emission lines and for two lines in the WC9-type spectrum of the central star (C III 4650 Å and 5696 Å). The ratio, shown in Fig. 2, is much higher in the blue with a steep rise below 4000 Å. The wavelength dependence agrees fairly well with that found by Pierce. The curve is much steeper than the scattering albedo for reflection nebulae around Population I stars derived by Witt *et al.* (1982) and Kurchakov (1968), which have roughly a $\lambda^{-1}$ dependence. This suggests that at least part of the 'aureole' observed at La Palma and Mount Wilson may be due to small particles in the atmosphere and telescope with a Rayleigh-type scattering law.

Although these observations are due to seeing effects we computed simple models to find the expected intensity from a reflection nebula. The assumptions are: spherical geometry with a radial dependence of dust density $N_d(r) \propto r^{-\beta}$, a single-scattering approximation, a power-law size distribution of grains with exponent $p = 3.5$ (Mathis, Rumpl & Nordsieck 1977) and scattering efficiencies $Q_{\rm sca}(\lambda)$ computed for silicate or graphite grains from the data of Draine (1985) and Draine & Lee (1984). The phase function was represented by the one-parameter Henyey–Greenstein (1941) formula. The solid curve in Fig. 2 shows the computed flux ratios

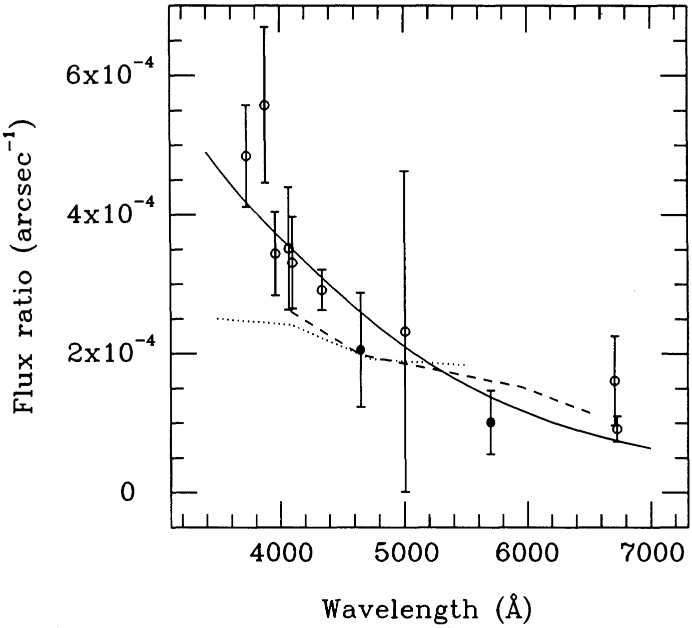

**Figure 2.** Ratio of scattered flux co-added along a slit (per arcsec of slit width) to total central object flux, as a function of wavelength, at an offset of 12 arcsec from BD + 30°3639. Open circles = nebular lines. Filled circles = emission lines in the central star's WR spectrum. Dashed and dotted lines = albedo for scattering around Population I hot stars derived by Witt *et al.* (1982) and Kurchakov (1968), respectively. Solid line = our best fit to the observed data using a circumnebular dust shell model, with grain-size range 0.005–0.08 μm (see text).

(offset/core) for the case of graphite grains with a size range 0.005–0.08 μm and $\beta = 3$. A similar good fit was obtained for silicate grains with a 0.005–0.13 μm size range, but we assumed graphite grains to be more appropriate since this nebula is carbon-rich, with $C/O > 1$ (Torres-Peimbert & Pena 1982). For the full size range of grains in diffuse clouds given by Mathis *et al.* (0.005–0.25 μm) a flatter colour variation is obtained, with slope similar to that observed around Population I stars (see Fig. 2). (In spite of their low abundance, the larger grains completely dominate the scattering, and their scattering efficiency varies roughly as $1/\lambda$.) Hydrogen-shell masses are derived here with our adopted grain parameters, which yield a phase-function asymmetry parameter $g = \langle \cos\alpha \rangle$ in the range 0.1–0.2. [Models in which the value of $g$ is forced to be ~ 0.7, as observed in known reflection nebulae (e.g. Witt *et al.* 1982), would have a dust mass about two times larger. This is because much of the emission seen comes from a scattering angle near 90°, while $g = 0.7$ corresponds to strong forward scattering.]

If the offset emission were taken as circumnebular reflection, the implied mass of graphite dust would be $4.4 \times 10^{-4}\ M_\odot$ and, together with a mean hydrogen-to-dust ratio for carbon stars of 400:1 by mass (Knapp 1985), this would correspond to a neutral shell of 0.18 $M_\odot$. However, this emission is consistent with light scattered by the Earth's atmosphere. Our data then provide an upper limit to the dust mass in a neutral zone around BD + 30°3639 of $\sim 2 \times 10^{-4}\ M_\odot$ with the assumptions given above. If this object does have an H I zone of gas, a larger dust mass would have been expected. Perhaps the dust-to-gas ratio is higher than, or the radial distribution of dust is quite different from, that assumed here.

### 3.2 NGC 7027

NGC 7027 has strong CO and $H_2$ emission (Mufson, Lyon & Marionni 1975; Treffers *et al.* 1976). Knapp & Morris (1985) derived a neutral shell mass of 1–2 $M_\odot$ from analysis of the

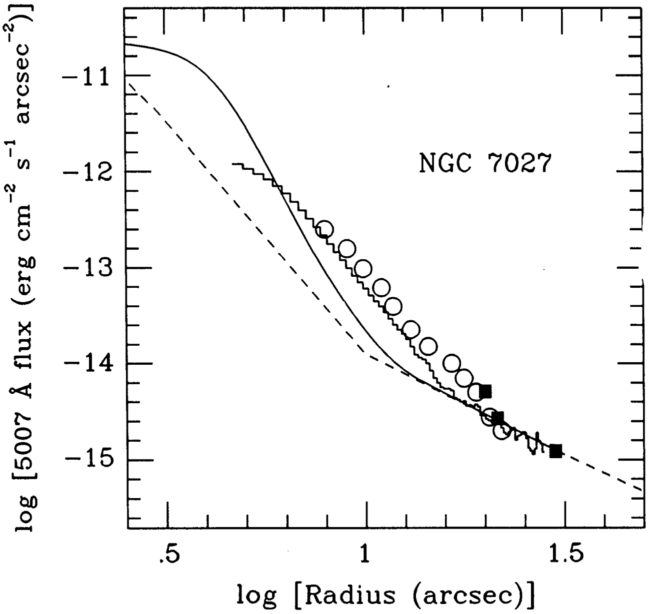

Figure 3. Radial surface-brightness profiles around NGC 7027. Circles = scaled H$\alpha$ profile from Atherton *et al.* (1979). Filled squares = our 1988 IPCS data for [O III] 5007 Å. Histogram = our 1988 CCD data, averaged from a number of offset positions. The solid line represents the convolution of a King profile with a uniform disc of radius 4 arcsec. The dashed line is the point source King profile. The total observed [O III] 5007 Å flux is $1.16 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$.

CO $J = 1 - 0$ line at 2.6 mm. Atherton *et al.* (1979) gave an image in H$\alpha$ whose faint outer halo suggested a reflection nebula around this object. Radio maps (e.g. Masson 1989) show an ellipsoid of major and minor diameters 12 and 8 arcsec. However, the differential extinction towards NGC 7027 (Walton *et al.* 1988) ensures that, in the optical, the effective size is smaller and is dominated by a bright patch west of centre. Fig. 3 shows two King profiles, one convolved with a disc of radius 4 arcsec, together with our IPCS and CCD data. The radial profile of the reflected light (Atherton *et al.* – their fig. 10) was only given as relative intensity, and we have scaled it to match their data with ours at an offset distance of 20 arcsec.

For this planetary there does appear to be emission in excess of the seeing and scattering profile between 12- and 20-arcsec offset. We fitted the excess in the CCD data (above the convolution with a 4 arcsec radius disc) with a model reflection nebula (computed as described above) for graphite grains with a size range from 0.005–0.25 $\mu$m and a $1/r^3$ density law. For a shell extending between 8 and 22 arcsec projected offset (with an assumed distance to NGC 7027 of 1.0 kpc, Masson 1989), the best fit provides a mass of dust of $3.8 \times 10^{-4}$ $M_\odot$. This corresponds roughly to a hydrogen mass of 0.15 $M_\odot$ for a hydrogen-to-dust ratio of 400. A $1/r^2$ density law produces the same mass of dust but does not fit the radial distribution so well. A preliminary conclusion is that the NGC 7027 reflection nebula may well be real, although new, well-calibrated quantitative images are required which can be analysed with the methods described here.

A cautionary note is sounded: observers taking such images should measure the scattered light from bright standard stars, and the effect of the broadening of the King function for an extended source must be taken into account. CCD images of stars, which are just as saturated as images of PNe, will have fainter aureoles for small offsets, as shown by Figs 1 and 3.

As a further example we show simple fits to some azimuthally-averaged H$\alpha$ + [N II] profiles presented by Jewitt *et al.* (1986) as potential detections of PN haloes. We have represented the 'cores' by simple, limb-brightened rings and convolved these with the King profile. Fig. 4 shows that while M1-64 and NGC 6894 do have extended haloes, Abell 53 needs to be analysed more carefully, with the image-broadening effects modelled properly, to establish a halo's presence. A simulation also shows that the faint halo outside NGC 3918 reported by Clegg *et al.* (1987) is probably due to scattered light.

## 4 The diffuse galactic background

This emission must also be taken into account in the search for PN faint haloes. It has been detected in the lines of H$\alpha$, [O III] 5007 Å, [S II] 6717, 6731 Å and [N II] 6584 Å (Reynolds 1985a,b; Reynolds & Ogden 1979) with typical flux ratios H$\alpha$:[O III]:[S II]:[N II] of 1:0.06:0.3:0.3. Mathis (1986) found that steady-state models of low-density gas ionized by distant O stars could reproduce these ratios, and predicted a flux for [O II] 3727 Å of ~ 3 times $I(\mathrm{H}\beta)$. Monk, Barlow & Clegg (in preparation) have modelled offset spectroscopic observations of IC 418 (at galactic latitude $b = +24°$), including measured [O II] doublet ratios, as the sum of scattered nebular light plus diffuse galactic emission.

As a final example we consider the possible *spectroscopic* detection of a faint halo around NGC 1535 in [O III] 5007 Å by Weller & Heathcote (1987). They report emission out to at least 60 arcsec, with surface brightness between $10^{-4}$ and $10^{-5}$ that of the main planetary. We used the H$\alpha$ surface brightness in the direction of NGC 1535 ($l = 206°$, $b = -40°$) measured by Reynolds & Ogden (1979), together with the average $I(5007)/I(\mathrm{H}\alpha)$ ratio given above to

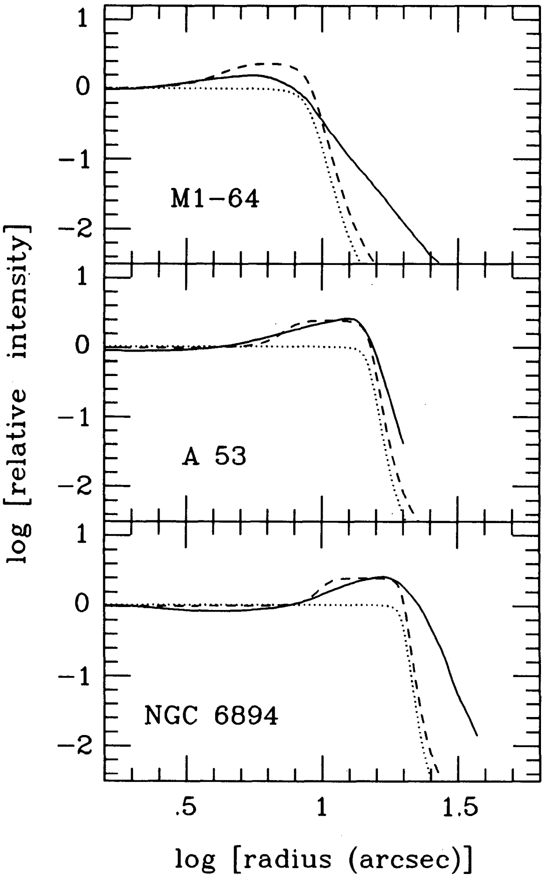

**Figure 4.** Radial intensity profiles of three PNe observed by Jewitt *et al.* (1986). Solid lines = observed profile in H$\alpha$ + [N II]. The other lines represent the convolution of a King profile with a central nebula, represented either as a uniform disc (dotted line) or (more realistically) as a limb-brightened disc having twice the intensity in the outer 40 per cent of the radius (dashed line).

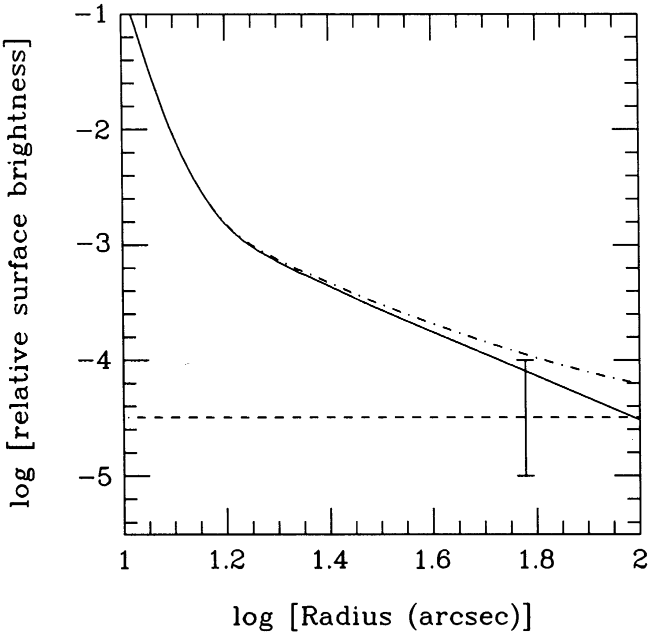

**Figure 5.** [O III] 5007 Å profile of a planetary of radius 9.2 arcsec (representing NGC 1535). Solid line = expected King profile. Dashed line = predicted galactic diffuse emission (see text). Dash–dot line = sum of these. Spectroscopic detection of λ5007 out to 60 arcsec offset was reported, with intensity $10^{-4}$ to $10^{-5}$ that of the central 'core' (represented by error bar).

predict a surface brightness in λ5007 of $5 \times 10^{-17}$ erg $cm^{-2}$ $s^{-1}$ $arcsec^{-2}$. The nebular absolute Hβ flux and reddening were taken as $F(H\beta) = 3.6 \times 10^{-11}$ erg $cm^{-2}$ $s^{-1}$ and $c(H\beta) = 0.1$ (Carrasco, Serrano & Costero 1983; Torres-Peimbert & Peimbert 1977). Fig. 5 shows surface-brightness profiles for NGC 1535, with the King profile convolved with a uniform disc of radius 9.2 arcsec (Weller & Heathcote 1987). The predicted level of the diffuse [O III] is indicated, and it can be seen that the reported emission is consistent with the sum of scattered light plus diffuse galactic emission. (The predicted diffuse level is an upper limit, as the [O III]/Hα flux ratio may be lower at high galactic latitudes, Reynolds 1985b). Of course, there may be a real halo, but it is necessary to demonstrate that observed emission is not due to one or both of these effects.

It should be noted that the best 'contrast' between halo emission and the diffuse background will usually be obtained for the [O III] 5007 Å line, as this is strong in most PNe while Hα and [O II] 3727 Å are strong in the background. Also, the diffuse emission is not restricted to low galactic latitudes: Mendez *et al.* (1988) attributed faint emission seen around six sdO stars to this background (one star had latitude $b = -74°$). Also, IC 418 has $b = +24°$.

## 5 Concluding remarks

Many PN haloes are real: for example, the classic giant haloes of NGC 6543 and 6826 (Middlemass, Clegg & Walsh 1989) and others found from images or in velocity space. We caution here about haloes found spectroscopically, where allowance must be made for light scattering and for the diffuse galactic background.

Two other techniques are important for establishing the presence of real haloes or reflection nebulae. Spectropolarimetric measurements of suspected reflection nebulae should be made, particularly for lines in the spectrum of BD + 30°3639 below 4000 Å. The linear polarization is likely to be high, as the scattering angle is near 90° (*cf.* the detection of polarized reflected light around IRC + 10°216 by Tamura *et al.* 1988). Secondly, high-resolution spectra which distinguish velocity shifts provide a powerful tool for confirmation of reflection nebulae. A high-altitude site, free of haze and dust and with clean telescope mirrors, is needed to minimize the local scattering effects discussed above.

## Acknowledgments

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## Note added in proof

C. R. Masson (*Astrophys. J.,* in press) recently measured the expansion of BD + 30°3639 with the VLA and found its distance to be 2.8 ( + 47, − 1.2) kpc. For a model dust shell of fixed mass and angular radius, an increase of distance from 1.1 to 2.8 kpc yields a reflection nebula surface brightness a factor 6.5 lower than the model result in Fig. 2. Our upper limit on the dust mass (Section 3.1) would then be 6.5 times larger, perhaps explaining the discrepancy at the end of Section 3.1.