Photometric Variations in LMC Planetary Nebulae

Richard A. Shaw (NOAO), Armin Rest (Harvard U.), Guillermo Damke (NOAO/CTIO)

Introduction

Variability in planetary nebulae (PNe) has been studied for many decades, with renewed interest in the past decade or so. Variability in a PN is often a strong indicator of a binary central star (CS), which can illuminate the role that binary stars play in the formation, morphology, and evolution of the nebula. The study of variability in large samples yields clues about the frequency of PNe with binary central stars (Bond 2000; Moe & DeMarco 2006). Historically, photometric variability in PNe has been attributed to a variety of interesting phenomena, including heating of the photosphere of the secondary by the hot central star (Bond 2000), obscuration by dust internal to the PN (Kato, et al. 2001), symbiotic systems (Lutz et al. 1989; Corradi, et al. 2001; Pena, et al. 2004), and to the interaction of a jet from the CS with the surrounding PN (Doyle, et al. 2000).

In spite of decades of investigation, the number of PNe with known variability is small, and the fraction of PNe with binary central stars is not known to useful accuracy. This is due in part to the rarity of PNe in stellar populations (owing to their short observable lifetimes), and because PNe with binary CSs do not necessarily exhibit detectable variability. Observationally, it has been very difficult to address the question of binary frequency because of the difficulty in assembling a large, complete sample of Galactic PNe and because the central stars are inherently faint, so that up to now it has been prohibitively expensive in telescope time to acquire the necessary data.

We have initiated a study of photometric variability for a large sample of PNe in the Large Magellanic Cloud (LMC). This project was enabled by the recent publication of a deep, wide-area Hα survey of PNe in the LMC (Reid & Parker 2006*a*, *b*; hereafter, the Reid-Parker survey), and by two wide-area time-domain surveys that covered nearly the same area. The intersection of the survey footprints includes ~450 PNe with highly accurate positions. The observing cadences and temporal baselines are sufficient to identify many binary central stars. The net result is a large, flux-limited, and volume-complete sample of PNe at known distance that has been monitored in brightness over a substantial period of time with high sensitivity.

The Time Domain Surveys

Two time-domain surveys have enabled this study: The MACHO survey (Alcock, et al. 1999) and the follow-on SuperMACHO survey (Rest, et al. 2005; Garg, et al. 2007). Although neither survey was intended for PN research, the surveys have complementary strengths for our purpose, as shown in **Table 1**. Both surveys covered a very large field, including most of the area of the Reid-Parker survey. While the temporal coverage of MACHO is longer and more regular, SuperMACHO is deeper and has significantly better image quality. Together, they cover a wide range in brightness and time.

As excellent a resource as these surveys are for studying PN variability, neither is *ideal* for the purpose and there are a few significant difficulties. The first is that the broad continuum filters used include bright nebular emission lines, so that it is not always obvious whether it was the nebula or the central star that was varying. In any case, the amplitude of any stellar variation is diluted because the nebular emission in these bandpasses can greatly exceed that of the central star. The second problem is that the cadence of the observations is not optimal for detecting variability on timescales of ~10 d or less, which is expected for post-common envelope binaries (see, e.g., Han et al. 1995). Third, even the Super-MACHO survey depth is too shallow to detect the faintest central stars (at *V* ~27) and some nebulae with very low surface brightness. Finally, unresolved background stars within the photometric aperture can dilute the light curves of the faintest CSs, although it is unlikely that background stars are themselves variable. Thus, it is important to note that *variability cannot be ruled out* except for the brightest PNe, and the fraction of PNe classified as variable from this work is a lower limit.

Summary of the Variability

A total of 448 PNe are located within the footprint of either or both of the MACHO and SuperMACHO surveys. Some of the nebulae were too faint to be detected and no central star was evident in many others. (Establishing the effective survey limit for detected PN central stars is the subject of ongoing work.) In this paper we focus on the majority of PNe that were detected, of which 29 show genuine signs of variability and another 26 show possible signs of variability. The more conservative total is still comparable to the number of confirmed variable PNe in the Galaxy to date.

In all we found six types of light curves among the PNe in the LMC, which are summarized in **Table 2**. Five of the curves are illustrated in **Figure 1** with data from SuperMACHO:

RP 980 is an example of an outburst event, which given the sudden brightening is undoubtedly stellar in origin. Only a lower limit to the outburst amplitude can be derived from the light curve, since the surrounding nebula contributes considerably to observed magnitude, and thus the detailed interpretation (e.g., recurring nova, CV, symbiotic) is ambiguous.

SMP 28 shows a slow decline in *VR* of ~0.4 mag per decade, which is a continuation of a decline that is evident in the MACHO data. This PN is angularly fairly small (Shaw et al. 2001) and perhaps young, so there are a number of possible interpretations, including an increase in CS surface temperature (at constant luminosity), dust formation in an extended atmosphere (causing increasing attenuation of the CS), or a decrease in the ionization of the surrounding nebula.

RP 1304 shows the clear signature of a recurring eclipse event, indicating fairly unambiguously the presence of a companion of stellar size.

RP 415 shows an unusual phenomenon: a slow, low-amplitude decline, followed by a slow return to approximately the initial flux. This type of curve could indicate dust within the PN passing between the CS and the observer, as was found for the Galactic PN NGC 2346 (Kato et al. 2001).

SMP 32 shows irregular variability, meaning no periodicity can be discerned but the magnitude of the variations substantially exceeds the photometric uncertainty. The short-term variations, if genuine, are almost certainly stellar in origin. Various investigators (e.g., Bond 2000) have identified PN central stars with companions having periods in the range 2.7 hr to a few days. Light curves such as that for SMP 32 may be detections of regular, short period variability that is temporally unresolved in these time-domain surveys.

The Unusual Variability of RP 916

A most unusual type of variability was discovered in RP 916, as described by Shaw et al. (2007). This nebula has a "butterfly" morphology with a dark lane bisecting the pinched main lobes of emission, as seen in Figure 2. It is among the largest PNe in the LMC, measuring over 1.72 x 0.74 pc at the distance of the LMC, with a substantial extension of faint nebulosity to the ENE. The emission is entirely nebular in origin, with a central star that is at least partially obscured within the dark lane. Reid (2007) obtained confirmatory spectra of RP 916, which show moderately low excitation, but with an ionization typical of a PN. The density is ~400 cm^-3, and the N abundance is probably not highly enriched. Its radial velocity of 280 km/s establishes its location in the LMC.

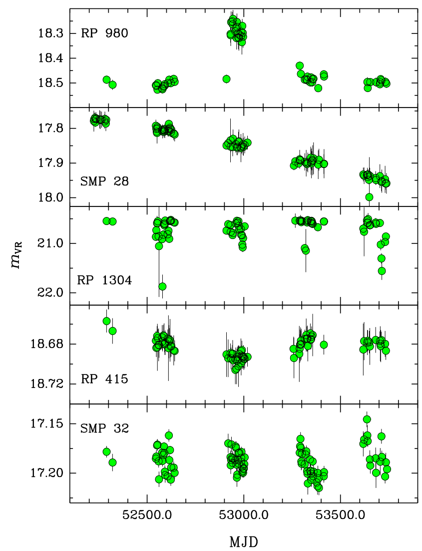

Figure 1.–Light curves from the SuperMACHO data illustrating five types of PN variability (*top to bottom*): **outburst** (RP 980), **slow decline** (SMP 28), **eclipse** (RP 1304), **slow variation** (RP 415), and **irregular** (SMP 32). Magnitude in the *VR* bandpass includes both stellar and nebular contribution. Another type of variability, arising in the nebula itself, was described by Shaw et al. (2007) and is illustrated in the next few figures.

Table 1.–LMC Time-Domain Surveys

Coverage	SuperMACHO	MACHO
Spatial		
Coverage:	23 deg^2	40 deg^2
DIQ:	0".8–2".0	2".0 (median)
Sampling:	0".27	0".64
Temporal		
Coverage:	2001 Oct.–2006 Jan.	1992 July–2000 Jan.
Cadence:	2-night period, 3 consecutive dark runs, 5 annual campaigns	Nightly
Photometric		
Bandpass:	*VR* (510–740 nm)	*B* (450–590 nm) *R* (590–780 nm)
Depth:	*VR* ~ 17.5–23.5	*R* ~ 12–20

Table 2.–Variability by Type

Type	Number
Outburst	5
Slow Decline	3
Eclipse	3
Slow Variation	3
Intra-nebular	1
Irregular	14
Possibly Irregular	26

Figure 2.–*HST*/WFPC2 image of RP 916. Nebular extent is more than 7″ x 3″ (1.72 x 0.74 pc). Image credit: P. Challis.

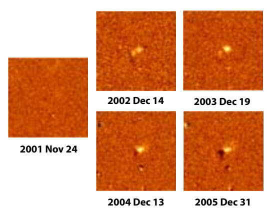

Figure 3.–False-color difference images of RP 916 from the indicated epochs. Images are 30″ x 30″ with N up and E left. Adapted from Shaw et al. (2007).

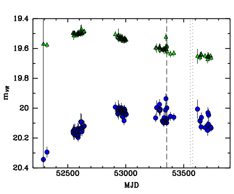

Figure 4.–Light curves for the eastern (*triangles*) and western (*circles*) lobes of RP916 in the SuperMACHO *VR* bandpass. The epoch of the template image is indicated (*solid line*), as is the epoch of the SAGE mid-IR campaign (*dotted lines*). Nebular diagnostics suggest a density of ~400 cm^-3, implying a recombination timescale of 300 yr; Shaw et al. (2007) suggest the variability may be caused by shock excitation from a precessing jet from a binary companion.

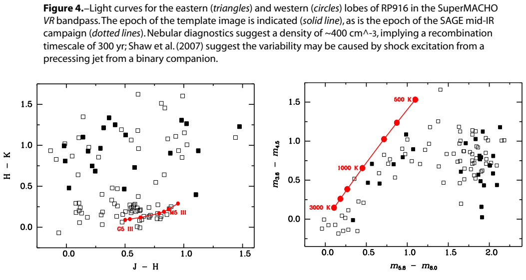

Figure 5.–Infrared color-color plots of PNe in the full sample (*squares*), with known or suspected variables indicated (*filled symbols*). Near-infrared colors (*left*) from 2MASS (Skrutskie 2006) are often inconsistent with Giant stars (luminosity class III; *red curve*), particularly for variable PNe, suggesting that emission from dust (and to some extent, nebular emission lines) dominates the spectrum. The mid-IR colors (*right*) from the SAGE survey (Meixner et al. 2006) suggest that, while the dominant dust emission is often thermal (see loci of black-body emission at various temperatures), a molecular emission (e.g., PAHs) is more important in a bit more than half the sample.

As illustrated in **Figures 3** and **4** the brightness of each lobe in RP 916 varied during the course of the SuperMACHO campaign, either independently, or similarly but with a phase lag of at least 1 yr. Nebular variability such as this is extremely unusual in PNe, and may indicate the presence of a binary CS. The variation is probably not from a global change in ionizing photons, as the inferred H recombination timescale is ~300 yr if the derived density is representative of the whole nebula. Shaw et al. (2007) suggest that the variability may result from a precessing jet of material from the central source that interacts with (i.e., shocks) the surrounding nebula. Other PNe that show a similar photometric variability, resulting from a symbiotic companion, are the Galactic bipolar PN He2–104 (Corradi et al. 2001), and SMP 83 (Pena et al. 2004). The variability observed within M2–9 was interpreted by Doyle et al. (2000) as an interaction of a jet from the central source interacting with the surrounding PN, which has over time continued to shape the nebular morphology.

The frequency of nebular variability generally within PNe is not known, but RP 916 may be the most extreme example of how PN morphology can be re-shaped even at very advanced stages of evolution. This type of variability may prove to be an excellent indicator of a binary system, even if the CSs cannot be directly observed. Photometric monitoring of a sizable sample of well resolved PNe is crucial for determining what fraction of PNe experience the unusual variability seen in RP 916.

Nature of the Companion Stars

Although variability has been the most common (and successful) technique employed to date for discovering binary central stars, the recent publication of source catalogs from the extended 2MASS near-IR survey, and the *Spitzer*/IRAC SAGE mid-IR survey (Meixner et al. 2006) have provided an important tool for discovering cool CS binary companions through their infrared excess. The limiting magnitude for the 2MASS survey is sufficient to detect Giant (luminosity class III) stars at the distance of the LMC (main sequence companions would not be detectable with this technique, however). Although more PNe in this sample were detected in the SAGE survey than in 2MASS, in the end slightly more than half of the PNe were detected in one or more bands of either survey. Those that were detected in all three of *J*, *H*, and *K*, and similarly those detected in all of the IRAC bands, are represented in the two color-color plots in **Figure 5**. While perhaps half of these nebulae have colors that are consistent with a Giant secondary star (except, notably, the bulk of the variable candidates), the others show signs of strong emission from dust. The SAGE data suggest that the dust emission from somewhat more than half of the PNe is dominated by non-thermal emission, presumably from complex molecules such as PAHs.

What may we conclude from these IR data? The possibility of impostors (i.e., foreground or background objects that are spatially co-aligned with the PNe) cannot be ignored. However, the astrometric accuracy of these catalogs is excellent (as it is for our targets: ~250 mas), and even the ~2″ PSFs for SAGE and 2MASS does not allow for many misidentifications, at least at these bright flux levels. Confirmation of the binary companions will require follow-up spectroscopy and (ideally) space-based IR imaging. While a search for Main Sequence companions is not yet within reach, perhaps the most important point is that we now have an excellent set of candidates in a flux-limited sample with which interesting and important constraints can set on the frequency of binary CSs. Further questions, such as whether binaries are *necessary* for the formation of detectable PNe await further investigation.

Conclusions & Future Work

Progress in the search for variability in PNe has up to now been slow in coming. But by leveraging excellent time-domain surveys and powerful image processing techniques we have discovered a population of variable PNe in the LMC that is comparable in number to that known for the Galaxy. In cases where the nature of the variation is unclear (e.g., a period in a close binary), follow-up campaigns are planned that at least have the advantage of knowing which targets to study. Since we are able to study a complete (flux limited) sample, this census, when complete, will be able to set meaningful, quantitative limits on the fraction of variable PNe in the LMC, and therefore on the number of PNe with binary companions. Although corrections for sample completeness have yet to be made, early indications are that the fraction of PNe that are variable cannot be less than 6% in the period–brightness range covered in these surveys. Further, we have not found evidence of a large population of binary nuclei with periods 10–100 d periods (Bond 2000), although our sensitivity limits may not be sufficient to detect variability in all such systems. Variability within a nebula, as in RP 916, can be a strong indicator of CS binarity. It is not known how common the RP 916 phenomenon is, but determining its origin may lead to greater understanding of how at least some PNe shape their morphology even at late evolutionary times. Finally, new IR catalogs have opened up a new window for detecting binary CSs, and early indications are that many candidates exist. Follow-up photometry on the candidates that show possible short-term variability is planned in the near future.

Support for this work was provided by NOAO, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NSF co-operative agreement NAS5–26555. The SuperMACHO survey was conducted under the auspices of the NOAO Survey Program. A.R. thanks the Goldberg Fellowship Program for its support. SuperMACHO is supported by STScI grants GO–10583 and GO–10903.

References

Alcock, C., et al. 1999, PASP, 111, 1539
Allen, C. W. 1999, Astrophysical Quantities, ed. A. Cox (4th ed.; New York: Springer-Verlag)
Bond, H. E. 2000, in ASP Conf. Ser. 199, Asymmetrical Planetary Nebulae II, ed. J. Kastner, N. Soker & S. Rappaport (San Francisco: ASP), 115
Corradi, R. L., M., et al. 2001, ApJ, 553, 211
Doyle, S., Balick, B., Corradi, R. L. M., & Schwarz, H. E. 2000, AJ, 119, 1339
Garg, A., et al. 2007, AJ, 133, 403
Han, Z., Podsiadlowski, P., & Eggleton, P. 1995, MNRAS, 272, 800
Kato, T., Nogami, D., & Baba, H. 2001, PASJ, 53, 901
Meixner, M., et al. 2006, AJ, 132, 2268
Moe, M. & DeMarco, O. 2006, ApJ, 650, 916
Lutz, J. H., et al. 1989, PASP, 101, 966
Pena, M., et al. 2004, AA, 419, 583
Reid, W. A., & Parker, Q. A. 2006*a*, MNRAS, 365, 401
Reid, W. A., & Parker, Q. A. 2006*b*, MNRAS, 373, 521
Reid, W. A. 2007, Ph.D. Thesis, Macquarie University
Rest, A., et al. 2005, ApJ, 634, 1103
Shaw, R. A., et al. 2007, ApJ, 669, L25
Shaw, R. A., et al. 2001, ApJ, 548, 727
Skrutskie, M. F., et al. 2006, AJ, 131, 1163