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# Photometric Variations in LMC Planetary Nebulae

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**Summary.** We present preliminary results of a search for photometric variability in a large sample of planetary nebulae (PNe) in the Large Magellanic Cloud. This survey was enabled by the extant data of the SuperMACHO survey at CTIO, and the MACHO survey at Mount Stromlo Observatory. Our exceptionally precise difference-image photometry and the long time baseline of the surveys allow us to detect photometric trends as small as 0.1 mag per decade. The survey footprint covers an area known to include  $\sim 450$  PNe. Our initial results suggest that variability in the frequency-brightness domain explored in these surveys is rather uncommon. The results of this project shed light on the fraction of PNe that are the progeny of binary central stars.

**Key words:** planetary nebulae — Magellanic Clouds — stars: variability — surveys: time domain

## 1 Introduction

Photometric 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 [4, 13]. Historically, photometric and spectroscopic variability in PNe has been attributed to a variety of interesting phenomena, including the evolution of the CS to high temperature [7], obscuration by internal dust [10], symbiotic systems [11, 5, 14], and to the interaction of a jet from the CS with the surrounding PN [6].

In spite of decades of investigation, the number of PNe with known variability is small (see, e.g., [4]), 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 any given stellar population (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  $H\alpha$  survey of PNe in the LMC [15] (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  $\sim 450$  PNe with positions that are known to  $\sim 250$  mas. The observing cadences and temporal baselines are sufficient to identify binary central stars with periods longer than  $\sim 7$  d, as well as long-term photometric changes as small as 0.1 mag per decade, which should be sufficient to detect the evolution of the more massive PN central stars to high temperature along constant luminosity tracks. 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.

## 2 The Time Domain Surveys

Two time-domain surveys with CCD cameras have enabled this study: The MACHO survey [2] and the follow-on SuperMACHO survey [17, 8]. 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.

**Table 1.** LMC Time-Domain Surveys

Coverage	SuperMACHO	MACHO
Spatial	23 deg <sup>2</sup>	40 deg <sup>2</sup>
DIQ:	0''8–2''0	2''0 (median)
Sampling:	0''27	0''64
Temporal	Oct. 2001—Jan. 2006	1992 July—2000 Jan.
Cadence:	2-night period, 3 consecutive dark runs, 5 annual campaigns	Nightly
Photometric	$VR$ (510–740 nm)	$B$ (450–590 nm) $R$ (590–780 nm)
Depth:	$m_{VR} \sim 17.5$ to 23.5	$R \sim 12$ to 20

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  $\sim 10$  d or less, which is expected for post-common envelope binaries (see, e.g., [9]). Third, even the SuperMACHO survey depth is too shallow to detect the faintest central stars (at  $m_V \sim 27$ ), nor 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.

Our search was enabled primarily by using the automated pipeline developed for the SuperMACHO project, which makes use of a very powerful difference image technique (see [1, 3]). In brief, all of the images are resampled to the same geometry and sky subtracted, and the images are placed on the same photometric scale. The PSF of a template image<sup>4</sup> is then matched to each target image via convolution, and subtracted. The difference image has the value 0.0 everywhere (apart from shot noise) except for features that are either fainter or brighter than those in the template image. Photometry is then performed at the position of the target on the difference image for each observation. This technique has been shown to yield accurate photometry even in crowded fields such as the LMC, and is extremely robust against non-photometric conditions.

### 3 Summary of 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 all of these are angularly extended [15], low surface brightness PNe) 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 interpretation (e.g., recurring nova, CV, symbiotic) is ambiguous. SMP 28 shows a slow decline in  $m_{VR}$  of  $\sim 0.4$  mag per decade, which is a continuation of a decline that is evident in the MACHO data. This PN is angularly fairly small [18] 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. RP1304 shows the clear signature of a recurring eclipse event,

<sup>4</sup> A template image for each field is selected based on the best seeing and photometric conditions during the campaign.

**Table 2.** Variability by Type

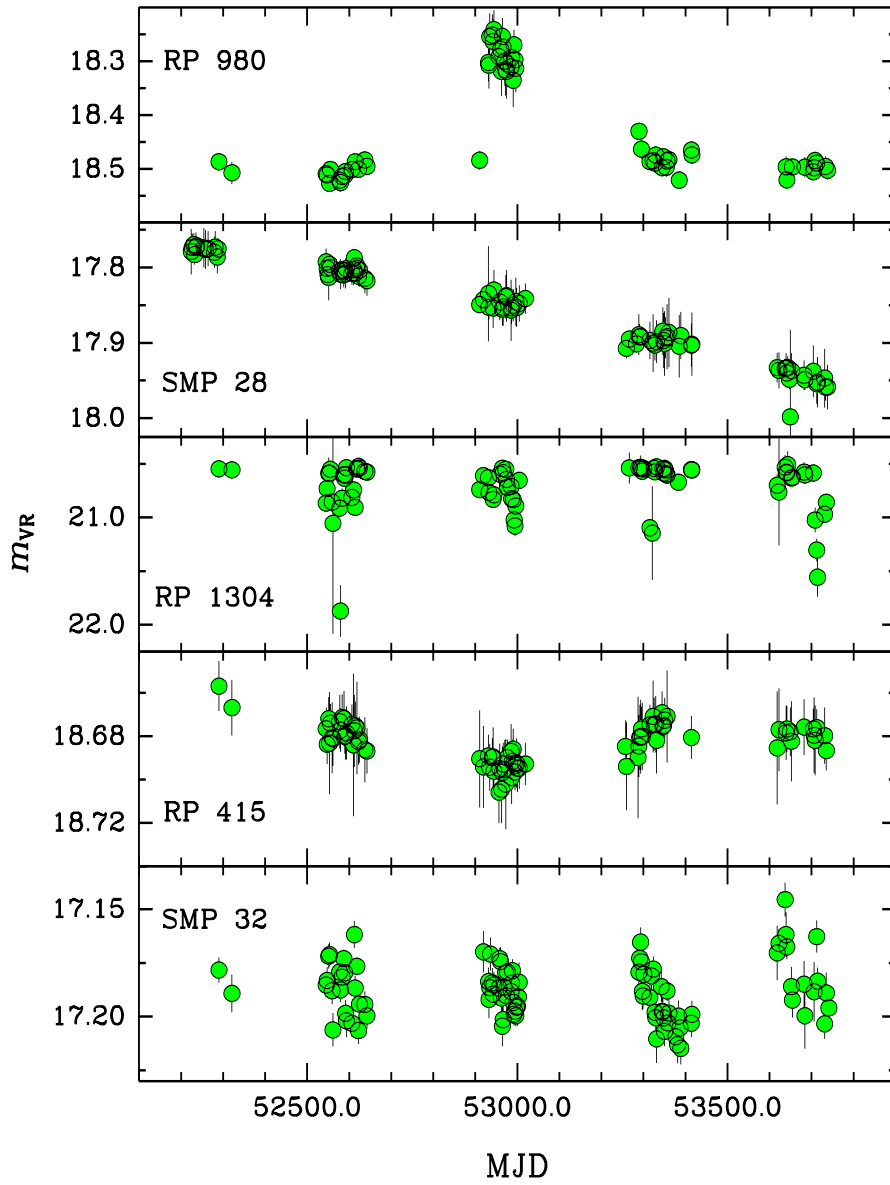
Type	Number
Outburst	5
Slow decline	3
Eclipse	3
Slow variation	3
Intra-nebular	1
Irregular	14
Possibly Irregular	26

indicating fairly unambiguously the presence of a companion of stellar size. RP415 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 NGC 2346 [10]. SMP32 shows irregular variability, meaning that 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 [4] 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 SMP32 may be detections of regular, short period variability that is temporally unresolved in these time-domain surveys.

#### 4 The Unusual Variability of RP916

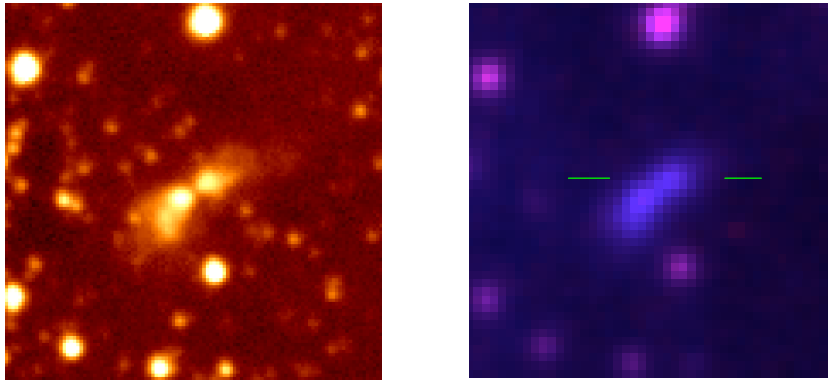
A most unusual type of variability was discovered in RP916, as described by [19]. This nebula has a “butterfly” morphology with a dark lane bisecting the pinched main lobes of emission, as seen in Figure 2. It is among the largest PNe in the LMC, measuring over  $7''.0 \times 3''.0$  (or  $1.72 \times 0.74$  pc at the distance of the LMC), with a substantial extension of faint nebulosity to the ENE of the geometric center of the nebula. The emission appears entirely nebular (see the right-hand panel of Figure 2), with a central star that is at least partially obscured within the dark lane. Reid [16] obtained confirmatory spectra of RP916, which shows moderately low excitation, but with an ionization typical of a PN. The density is  $\sim 400 \text{ cm}^{-3}$ , and the N abundance is probably not highly enriched. These attributes leave little doubt that RP916 is a genuine PN, and its radial velocity of  $280 \text{ km s}^{-1}$  establishes its location in the LMC. RP916 is a strong source in both the 2MASS catalog [20] and the SAGE mid-IR catalog [12], indicating a substantial quantity of dust emission.

As illustrated in Figure 3 the brightness of each lobe in RP916 varied during the course of the SuperMACHO campaign, either independently, or similarly but with a phase lag of at least 1 yr [19]. Nebular variability such as this is extremely unusual in PNe, and may indicate the presence of a binary CS. One possibility is that the variation resulted from an outburst from a red companion, where the change in optical luminosity is manifested in the nebula as a light echo seen in scattered light from dust within the nebula. (Note that the phase lag of  $\sim 300 - 500$  d between the peak emission of the two lobes in Figure 3 would imply a significant inclination



**Fig. 1.** Light curves from the SuperMACHO data illustrating five types of PN variability (*top to bottom*): outburst, slow decline, eclipse, slow variation, and irregular. Magnitude in the *VR* bandpass includes both stellar and nebular contributions.

out of the plane of the sky.) However, no Mira-like periodicity is detected over the 1450 d observing campaign. The variation is probably not from a global change in ionizing photons, as the inferred H recombination timescale is  $\sim 300$  yr if the derived density is representative of the whole nebula. On the other hand [19] suggests 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 [5], and LMC-SMP 83 [14]. The variability observed within M2-9 was interpreted by [6] 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. While this mechanism is an interesting possibility for RP916, confirmation would require follow-up IR spectroscopy and regular, high-resolution imaging in the optical and IR.

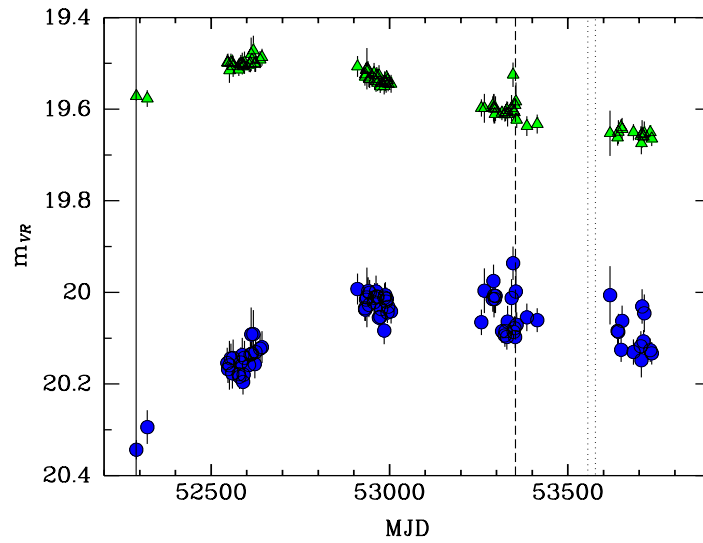


**Fig. 2.** Images of RP916 in the SuperMACHO  $VR$  bandpass (*left*), and in the AAO/UKST  $H\alpha + R$  continuum (*right*). Images are  $30'' \times 30''$  with north up and east to the left. The nebula is indicated in the  $H\alpha + R$  image: pure emission lines are rendered as blue, and continuum sources are rendered in pink.

The frequency of nebular variability generally among PNe is not known, but RP916 may be the most extreme example of how PNe morphology can be re-shaped even at very advanced stages of evolution. In any case 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 RP916.

## 5 Conclusions

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



**Fig. 3.** Light curves for 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 optical spectrum (*dashed line*) and the SAGE mid-IR campaign (*dotted lines*).

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 will 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 of 10–100 d (as suggested by Bond [4]), although our sensitivity limits may not be sufficient to detect variability in all such systems. Finally, variability within a nebula, as in RP916, can be a strong indicator of CS binarity. It is not known how common the RP916 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.

Support for this work was provided by NOAO, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NSF cooperative 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.

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