THE UNUSUAL VARIABILITY OF THE LARGE MAGELLANIC CLOUD PLANETARY NEBULA RPJ 053059−683542

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ABSTRACT

We present images and light curves of the bipolar planetary nebula RPJ 053059−683542 that was discovered in the Reid-Parker AAO UKST Hα survey of the Large Magellanic Cloud. The emission from this object appears entirely nebular, with the central star apparently obscured by a central band of absorption that bisects the nebula. The light curves, which were derived from images from the SuperMACHO project at CTIO, showed significant, spatially resolved variability over the period 2002 January through 2005 December. Remarkably, the emission from the two bright lobes of the nebula vary either independently or similarly but with a phase lag of at least 1 yr. The optical spectra show a low level of nebular excitation, and only modest N enrichment. Infrared photometry from the 2MASS and SAGE surveys indicates the presence of a significant quantity of dust. The available data imply that the central star has a close binary companion and that the system has undergone some kind of outburst event that caused the nebular emission to first brighten and then fade. Further monitoring, high-resolution imaging, and detailed IR polarimetry and spectroscopy would uncover the nature of this nebula and the unseen ionizing source.

Subject headings: Magellanic Clouds — planetary nebulae: general — stars: evolution

Online material: color figure

1. INTRODUCTION

Variability in the nuclei of planetary nebulae (PNe) has been studied for decades, with renewed interest in the past few years in order to understand the frequency of PNe with binary central stars (CSs; e.g., Bond 2000; Moe & De Marco 2006) and the role they might play in shaping the host nebula morphology and evolution. Variability within the nebulae themselves is less commonly reported but when present has been attributed to a variety of causes. For example, Feibelman et al. (1992) attributed changes in excitation of the nebulae IC 4997 and NGC 6572 to an increase in the temperature of the CSs; and Kato et al. (2001) reported two episodes of a deep fading and consequent brightening of the CS of NGC 2346, which they attributed to dust clouds within a PN passing in between the CS and the observer. More recently, Doyle et al. (2000) described the remarkable morphological evolution and photometric variation of M2-9, which they attributed to the interaction of ejected matter between a jet from the CS and the surrounding PN; Lutz et al. (1989) and later Corradi et al. (2001) argue from detailed UV and optical spectroscopy and IR photometry that He2-104 is a PN with a symbiotic (white dwarf plus a Mira variable) CS; and Peña et al. (2004) obtained extensive UV and visual-band spectra of the complex nebula LMC-SMP 83, which they attribute to episodic bipolar ejections from a nondegenerate secondary in a close orbit with a white dwarf.

We have initiated a study of photometric variability in Large Magellanic Cloud (LMC) PNe in order to make use of a very large, complete sample to set limits on the fraction of PN CSs that have companions of some sort and to explore the frequency of other patterns of variability. We have used data from the extensive SuperMACHO photometric survey at Cerro Tololo Inter-American Observatory (CTIO) of the LMC, which was obtained over a 4.2 yr period from 2002 through the end of 2005 (see Garg et al. 2007). One object, RPJ 053059−683542 (hereafter referred to by its common catalog name, RP 916), was found to have spatially resolved variability, which is a highly unusual phenomenon that to date has only one other rough analog: the variability in the Galactic PN M2-9. RP 916 was discovered by Reid & Parker (2006) in the Anglo-Australian Observatory (AAO) United Kingdom Schmidt Telescope (UKST) deep Hα survey of the LMC, who classified it as a “true” PN based on its morphology and spectral characteristics. It is one of the largest PNe known in the LMC and has a bipolar morphology. Aside from the near uniqueness of the phenomenon, this type of variability is highly suggestive of an interaction of the PN CS with an otherwise undetectable binary companion.

We describe in § 2 the extant observations for RP 916, including the photometric campaign, optical spectroscopy, and broadband IR photometry from the Two Micron All Sky Survey (2MASS) catalog and from the Surveying the Agents of a Galaxy’s Evolution (SAGE) survey with the Spitzer Space Telescope. We analyze the characteristics of the variability in § 3 and suggest interpretations that are most consistent with the observations in § 4.

2. OBSERVATIONAL DATA

Even before Reid & Parker (2006) reported the initial discovery, a good deal of ground- and space-based data had accumulated on RP 916, including broadband optical and infrared images and optical spectra. Interestingly, the bulk of the observations were obtained during the course of surveys of the LMC that were designed with purposes other than PN research in mind.

The primary optical images that were used for this study were obtained as part of the SuperMACHO survey of a 23 deg2 region centered on the bar of the LMC (see Rest et al. 2005; Garg et al. 2007 for details of the observing campaign). Eighty-two images in the vicinity of RP 916 were obtained with the Mosaic-II CCD camera on the Blanco 4 m telescope at CTIO between 2002 January and 2005 December. Most images were taken with a broad VR filter with a passband that covers 510–740 nm and includes the strong nebular emission lines such as Hα and [N ii] λλ6548, 6583, but avoids [O iii] λλ5007. This wide bandpass enabled the detection of faint objects (mVR ~
17.5–23.5) within the typical 150 s exposures of the survey. The CCD plate scale is 0.27″ pixel⁻¹, which samples the point-spread function (PSF) very well: the delivered image quality varied from roughly 0.8″ to 2.0″ over the course of the observing campaigns. An atmospheric dispersion corrector was used to minimize the differential atmospheric dispersion through the broad filter at the typical air mass of 1.3–1.4.

The SuperMACHO data were processed with an automatic pipeline (Garg et al. 2007; Miknaitis et al. 2007) that corrects for electronic cross talk between the amplifiers, removes the bias level, and applies a flat field. The images were reprojected to a common geometry, with an rms accuracy of ≈80 mas. The PSFs are then matched, and the images are corrected for sky background and placed on a common photometric scale prior to template subtraction. The template image (see § 3) is shown in the left-hand side of Figure 1 and was selected on the basis of the good image quality (≈0.8″) and the excellent photometric quality of the night on which this image was obtained.

The discovery images used by Reid & Parker (2006) were obtained as part of an AAO UKST deep photographic survey in Hα and in the R-band continuum and were obtained between 1998 and 2000. The 70 Å bandwidth of the Hα filter also includes the [N ii] emission lines at λλ6548, 6583. The photometric depth of the stacked images is ≈21.5 in R and R_{equi} ≈ 22 for Hα. The digitized images were sampled at 0.67″ pixel⁻¹, and the image resolution is roughly 3.5″. As described by Reid (2007), the stacked Hα and R-band images were each assigned a specific color in the final image: red for continuum, and blue for Hα. The discovery image of RP 916 is shown in the right-hand side of Figure 1.

Fortuitously, additional images were obtained by one of us (A. R.) with the *Hubble Space Telescope* (HST) using the Wide Field Planetary Camera 2. These images were obtained to study a microlensing target, but happened to include RP 916 at the edge of the field of view. In all, four images were obtained on 2007 May 17: U9PX0601M and U9PX0602M with the F555W filter and U9PX0603M and U9PX0604M with the F814W filter. The exposure times were all 500 s. We combined the calibrated images for each filter to improve the signal-to-noise ratio and to remove cosmic rays. The F814W image is shown in Figure 2.

Reid & Parker (2006) obtained two confirmatory spectra of RP 916 on 2004 December 14 with the Two Degree Field fiber spectrograph on the Anglo-Australian Telescope: one with a dispersion of 4.3 Å pixel⁻¹ and the other with a dispersion of 1.1 Å pixel⁻¹. The higher dispersion spectrum was used to resolve close emission-line blends and to determine the radial velocity. Since the angular size of the nebula exceeds the areal coverage of the fiber, the spectra actually correspond to the western lobe of RP 916. The spectra show moderately low excitation, with \( F([\text{O iii}]\lambda5007)/F(\text{Hβ}) \sim 2.4, \) relatively strong [O i] \( \lambda6300 \) and [O ii] \( \lambda3727 \), weak [O iii] \( \lambda4363 \), no detectable He ii emission, and moderate [N ii] with \( F(\lambda(6548 + 6583))/F(\text{Hα}) \sim 0.5 \).

RP 916 is a moderately strong infrared source (for a PN in the LMC), based on the 2MASS J, H, K magnitudes (Skrutskie et al. 2006) that were obtained on 2000 February 20 (MJD 51,602). It was also detected in the mid-IR SAGE survey with the *Spitzer Space Telescope* (Meixner et al. 2006) in the 3.6, 5.8, and 8.0 μm...
bands with the Infrared Array Camera (IRAC) and the 24 μm band with the Multiband Imaging Photometer for Spitzer (MIPS; the 70 and 160 μm band catalog data have yet to be published). The first epoch SAGE observations were obtained during 2005 July 15–26, around MJD 53,570. The IR brightnesses are given in Table 1.

3. ANALYSIS

All of the optical images show that RP 916 has a “butterfly” bipolar morphology (Balick & Frank 2002), with a dark lane (0.46", or 0.11 pc, in width) bisecting the pinched main lobes of emission. The extent of the nebula is 7.0′ × 3.0′ (1.72 × 0.74 pc at the distance of the LMC) as measured from a contour at 10% of the peak nebular brightness in the F814W image; the extent is roughly twice as large when measured just above the sky level, with a substantial extension of faint nebular material to the east-northeast of the geometric center of the nebula. The Hα + R color image shows that the emission is almost entirely nebular: what little continuum is evident in the R-band image undoubtedly originates from a combination of nebular continuum, emission lines in the R bandpass, and the few very faint field stars that are seen in the HST image. Interestingly, a faint star is evident in the F814W image, within the waist of RP 916, offset by ~0.23″ from the symmetry axis defined by the optical emission. The star is barely visible in the F555W image, however, indicating that it is intrinsically very red or suffers heavy extinction from dust within the waist of the nebula. It is not clear whether this is the CS of the nebula. The more detailed HST images show clumps of emission, with the brightest knots or lobes extending almost symmetrically to the east and west but not intersecting at the geometric center of the nebula. The appearance of RP 916 in the 2MASS images is that of an extended point source, with no sign of bilobed structure; the object is not resolved in the Spitzer IRAC or MIPS images. Although the confirmatory spectra of Reid & Parker (2006) are neither deep nor well calibrated to support a detailed abundance analysis, Reid (2007) derived an approximate density for RP 916 of ~400 cm⁻³ from the [S II] λ6716, 6731 line ratio. The amount of extinction, while only roughly determined, appears to be higher than average (c ~ 0.9) for an LMC PN; given the strong IR emission, some of the extinction may be intrinsic to the nebula. Finally, the modest ratio of F([N II]) / F(Hα) suggests that N is not highly enriched.

The various, general properties of RP 916 are summarized in Table 2.

The original point of our work was to search for variability in PNe. This search was enabled by using the automated pipeline developed for the SuperMACHO project, which makes use of a very powerful difference image technique (see Alard & Lupton 1998; Becker et al. 2004). 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 the template image is then matched to each target image via convolution and subtracted. The result of this subtraction on four selected nights is shown in Figure 3, where the difference 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 positions of the lobes 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 nonphotometric conditions.

Light curves were determined for the eastern and western lobes of RP 916, which are shown in Figure 4. Note that both lobes increased in brightness compared to the template image, but some time after the second year of the observing campaign the eastern lobe began to fade while the western lobe continued to brighten. By MJD ~ 53,200 = 2004 July, the western lobe began to fade, but more slowly than the eastern lobe.

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Fig. 4.—Light curves for eastern (triangles) and western (circles) lobes of RP 916. The abscissa shows 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). [See the electronic edition of the Journal for a color version of this figure.]

Figure 3 suggests that the orientation of the brightness enhancement in the western lobe changed and became elongated by MJD ~ 53,735 = 2005 December. The western lobe brightened by nearly 40% during the course of the observing campaign.

4. DISCUSSION

RP 916 is unusual in many respects, including its large physical size, strong IR emission, and optical variability. But the morphology and moderate ionization spectrum leave little doubt that it is a genuine PN, and the measured radial velocity establishes its location in the LMC. If the CS of RP 916 has a binary companion that is very red and luminous, it could contribute to the near-IR continuum luminosity, but it cannot account for the extreme colors in the mid-IR. Note, however, that since the epochs of the 2MASS and SAGE observations differ by 5.4 yr, it is possible that the ratio of the near- to far-IR luminosity could have changed somewhat during that time. We conclude that RP 916 contains a large amount of dust (which might be expected given the pinched waist and dark band that bisects the nebula). If RP 916 is similar to other LMC PNe with significant dust, both molecular emission features and thermal continuum radiation contribute substantially to the total IR flux, particularly in the mid-IR (see, e.g., Stanghellini et al. 2007).

The nebular variability is the most unusual feature of this object, and it is difficult to think of a cause that does not involve a binary star as the central engine. Indeed, the lack of an extreme N enrichment, which is typical of bipolar PNe in the LMC (Shaw et al. 2006), is consistent with common-envelope evolution, where the expected conversion of C to N via hot-bottom burning is suppressed. It may be that the variation resulted from an outburst from a red companion. In this case, a change in optical luminosity might be manifested in the nebula as a light echo seen in scattered light from dust within the nebula. (Note that the phase lag of ~300–500 days between the peak emission of the two lobes in Figure 4 would imply a significant inclination out of the plane of the sky.) However, no Mira-like periodicity is detected over the 1450 day observing campaign. It seems unlikely that the variation is 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. In any case, a light echo cannot explain the radial structures that are evident in the detailed HST images. The variability might, on the other hand, 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 LMC-SMP 83 (Peña et al. 2004). Doyle et al. (2000) interpreted the variability within M2-9 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 RP 916, confirmation would require long-slit spectroscopy to measure the velocity field, high-resolution (~0.1") or better imaging in Hα to reveal the time-dependent morphology of the variability, imaging polarimetry to measure the extent of any scattered light by dust, and infrared spectra to understand the nature of the IR luminosity and (possibly) detect a red, luminous companion star.

The frequency of nebular variability generally among PNe is not known, but RP 916 may be the most extreme example of how PN morphology can be reshaped even at very advanced stages of evolution. Photometric monitoring at high spatial resolution of a sizable sample of bipolar PNe in the LMC is crucial for determining what fraction of PNe experience the unusual variability of RP 916. Perhaps the observing campaigns of the next generation of survey telescopes such as that for the Large Synoptic Survey Telescope, which will have the necessary depth, sky coverage, and cadence, can help to resolve this broader question.

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