CIRCUMSTELLAR ENVIRONMENT
OF RX PUPPIS∗

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Abstract The symbiotic Mira, RX Pup, shows long-term variations in its mean light level due to variable obscuration by circumstellar dust. The last increase in extinction towards the Mira, between 1995 and 2000, has been accompanied by large changes in the degree of polarization in the optical and red spectral range. The lack of any obvious associated changes in the position angle may indicate the polarization variations are driven by changes in the properties of the dust grains (e.g. variable quantity of dust and variable particle size distribution, due to dust grain formation and growth) rather than changes in the viewing geometry of the scattering region(s), e.g. due to the binary rotation.

1. INTRODUCTION

RX Pup is a symbiotic binary composed of a long-period Mira variable pulsating with \( P \approx 578 \) days, surrounded by a thick dust shell, and a hot \( \sim 0.8 M_\odot \), white dwarf companion which has been undergoing a

∗to appear in Post-AGB objects as a phase of stellar evolution, eds. R. Szczerba et al., Kluwer
nova-like eruption during the last three decades. The binary separation could be as large as $a \geq 50$ a.u., and the corresponding $P_{\text{orb}} \geq 200$ yr, as suggested by the permanent presence of a dust shell around the Mira component (Mikołajewska et al. 1999, hereafter M99). In particular, the Mira is never stripped of its dust envelope, and even during relatively unobscured phases the star resembles high-mass loss galactic Miras with thick dust shells.

Our recent analysis of multi-frequency observations shows that most, if not all, photometric and spectroscopic activity of RX Pup in the UV, optical and radio range is due to activity of the hot component, while the Mira variable and its circumstellar environment is responsible for practically all changes in the IR range (M99). In particular, we have found large changes in the reddening towards the Mira accompanied by fading of the near IR flux (Fig. 1). However, the reddening towards the hot component and emission line regions remained practically constant and is generally less than that towards the Mira. These changes do not seem to be related to the orbital configuration nor to the hot component activity. Similar dust obscuration events occur in many well observed symbiotic Miras (e.g. Whitelock 1998), as well as in some single Miras (e.g. Mattei 1997, Whitelock 1998), and they are best explained as intrinsic changes in the circumstellar environment of the Mira variable, possibly due to intensive and variable mass loss (see also discussion in M99, and Mikołajewska 1999).

In the following we discuss polarization measurements for RX Pup obtained during the most recent obscuration phase.

2. OBSERVATIONS

$UBVRI$ polarization measurements were obtained between May 1996 and March 2000 with the five channel photopolarimeter of Turin Observatory, attached at the 2.15-m CASLEO telescope at San Juan, Argentina. More details about the instrumentation and data reduction can be found in Brandi et al. (2000). In addition, optical spectra with the same telescope and REOSC echelle spectrograph were obtained (see M99 for details). Finally, new $JHKL$ broad-band photometry on the SAAO system was obtained with the MkII infrared photometer on the 0.75-m telescope at Sutherland (Carter 1990). These new IR data together with data from M99 are displayed in Figure 1 where the dates of the polarimetric measurements are also marked.
3. RESULTS AND DISCUSSION

In the period covered by our polarimetric observations, the near IR flux of RX Pup was gradually decreasing and the $J - K$ colour was increasing, suggesting that the Mira had entered a new obscuration phase. These secular changes in near IR flux are generally not correlated with changes in the optical; in particular the visual magnitude estimates reported by the Variable Star Section of the Royal Society of New Zealand (RASNZ) show that RX Pup was brightening in the optical between 1995 and 1998, and declining later (see also Fig. 4 in M99).

![Figure 1](image)

Figure 1  $J$ and $L$ light curves and $J - K$ colour of RX Pup. The upper panel show the same light curves after removal of the Mira pulsation. Bars in the bottom panel indicate dates of our polarimetric observations.

The results of polarimetric observations are shown in Figure 2. The left panel presents the degree of polarization and the position angle as a function of wavelength for different observing runs. The observed wavelength dependence of $p$ and the position angle could be accounted for by the presence of two components, one with p.a. $\sim 145 - 155^\circ$, and a flat wavelength dependence resembling that of interstellar polarization which suggests a presence of interstellar-type large dust particles, and another component with p.a. $\sim 175 - 160^\circ$ and $p$ increasing steeply
towards the ultraviolet, consistent with Rayleigh scattering by small particles. Both components show significant temporal changes which indicate circumstellar origin of the observed polarization.

Figure 2 also shows the polarization changes versus the visual magnitudes and $J-K$ colour. The visual magnitude is dominated by the light from the hot component, whereas the $J-K$ colour measures the amount of reddening towards the Mira component. The polarization degree seems to increase with both the visual magnitude and the $J-K$ colour. At the same time we do not find any correlation between the polarization and the Mira pulsation phase.

The polarized flux does not seem to be scattered light from the Mira, since in the optical the Mira is heavily obscured by the dust (M99). In particular, we do not see pulsational variations, nor can we detect the TiO bands in optical spectra at any epoch (see also M99). The $UVBR$ and probably also the $I$ flux is dominated by the hot component with some contribution from the nebular line and continuum emission. M99 also found that the contribution from the nebular emission increases relative to other sources of emission as the optical brightness decreases, and as the hot component temperature and degree of ionization in the nebula increase. In particular, the contribution from the nebular emission was negligible in 1995-1996. Then the relative contribution of the nebular emission increased from mid 1998 in-step with the declining visual brightness, although it never exceeded 0.1-0.15 mag. The polarized flux varied by a factor of $\sim 2$ in the visual range, whereas the strongest $\text{H}\beta$ Balmer and Fe$\text{ii}$ emission-line fluxes remained constant within $\sim 20\%$.

There was also no significant increase in polarization (although only $p_R$ estimates are available) in 1987, when the nebular continuum and emission lines where much stronger than in the 1990s (M99). It is thus unlikely, that the polarized component corresponds to the nebular emission. Instead we believe that it is most likely to be radiation from the warm, $T \sim 6000\,\text{K}$, component found in the 1995-96 optical spectra by M99 – scattered in the dust envelope surrounding the Mira. The warm component is responsible for the optical variability in the 1990s; however, there is no obvious, simple correlation between this activity and the reported polarization changes.

The changes in polarization are apparently correlated with the varying reddening towards the Mira. Between 1994/5 and 1999/2000 the Mira’s average brightness weakened by $\sim 1.5$ mag at $J$ and $\sim 0.7$ mag at $K$, respectively. The mean $J-K$ colour increased from $\sim 2.2$ in 1994/5 to $\sim 2.6$ in 1996–98, and to $\sim 3$ in 1999, respectively. These changes have been accompanied by an increase in $p$, by a factor of $\sim 2 - 3$, at all wavelengths, and a slow rotation in the position angle. The sense of
Figure 2  Left: Wavelength dependence of linear polarization, $p[\%]$ (top), and position angle for different epochs (bottom). The points correspond to weighted mean values calculated for each observing run. The error bars are not shown, however the relative mean errors in $p[\%]$ are $<0.06$ in $UB$, $<0.008$ in $VRI$, and $<0.01$ in the position angle. Right: Dependence of the polarization on the reddening towards the Mira measured by the $J – K$ colour (top), and visual brightness (bottom).

This rotation, however, depends on the spectral range: the position angle decreased by $\sim 15^\circ$ in $UB$ and increased by $\sim 10^\circ$ in the $VRI$ range, respectively. Unfortunately, it is practically impossible to distinguish between a steady rotation of position angle with time and changes related to variable conditions in the circumstellar envelope of RX Pup because the reddening has been steadily increasing during the period covered by our observations.

There are very few previous polarization measurements for RX Pup. The $UBV$ polarimetric measurements obtained during maximum of the hot component outburst and IR bright phase of the Mira in 1979-1980 show practically flat wavelength dependence with $p \sim 2\%$ and a constant position angle of $\sim 120^\circ$ (Barbier & Swings 1982); however, these data were corrected, by an unknown amount, for interstellar polarization. In
any case, the component with $p$ steeply increasing towards ultraviolet was absent at this epoch. Schulte-Ladbeck et al. (1990) estimated $p_R = 1.61$ and p.a. $= 121^\circ$ on Mar 27, 1987, whereas Harries & Howarth (1996) measured $p_R = 1.825$ and p.a. $= 146.7^\circ$ on May 6-10, 1994. On both of these dates, the visual magnitude of RX Pup was $V/m_{\text{vis}} \sim 11.1$ and $J - K \sim 2.5$. We have observed similar values of $p_R \sim 1.5 - 1.6$ and $J - K \sim 2.5 - 2.7$ in 1996-98; the system was then, however, much brighter, $V \sim 10.4 - 10.1$. This may suggest that the polarization changes are related predominantly to changes in the reddening towards the Mira, and not to the hot component brightness. The polarization changes are also not related to any particular changes in the emission line spectrum of RX Pup.

Interestingly, during 1996 March to 1998 April the degree of polarization at $BVRI$ was practically constant, while in $U$ it varied. This may indicate that the 1996-98 changes were caused by variable conditions in the region where small particles dominate, while in 1999-2000 the contribution of large dust particles becomes comparably important. The lack of dramatic changes in the position angle associated with changes in $p$ and the reddening towards the Mira component may indicate the polarization variations are driven by changes in the properties of the dust grains, for example variable amounts of dust with variable size distributions, due to dust grain formation and growth.

If the rotation in position angle with time is due to orbital motion, than the change in p.a. of $\sim 10 - 15^\circ$ in $\sim 5$ years corresponds to the binary period of $\sim 120 - 180$ years. Similarly, $\Delta$ p.a. $\sim 30$ between 1987 and the most recent observations is consistent with $P \sim 160$ yr. Note that an orbital period of $\sim 200$ yr is also implied by the properties of the dust envelope around the Mira component (M99).

In this context, it is interesting that a similar increase in $p$ at $UBVRI$, together with a slow rotation of the position angle, increasing in $UB$ and decreasing in $RI$, was observed during the dust obscuration event in R Aqr in the late 1970s (Nikitin & Khydyakova 1979). There is, however, a significant difference between R Aqr and RX Pup; in the former the optical and red light is dominated by the Mira, whereas in the latter the contribution from the Mira is negligible at these wavelengths. Moreover, in R Aqr, both the degree of polarization and the position angle (especially in the ultraviolet and blue spectral range) also vary with pulsation phase, which is not the case for RX Pup.

Since we do not know the orbital phase of RX Pup, it is impossible to drive any definite conclusions from the position angle of the polarized light. However, the fact that the hot component does not seem much affected when the reddening towards the Mira is strongly increasing
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(M99), suggests that it cannot be behind the dust cloud. Furthermore, the relatively large degree of polarization suggests that it is to one side of, rather than in front of, the dust. Assuming that the dust around the Mira is largely confined to a cone shaped region, the hot star is not far from the quadrature and is moving in our direction (somewhere between the quadrature and the inferior conjunction). According to the standard scattering model the position angle of the polarized light should be roughly orthogonal to the line connecting the source of light and the scattering region. The observed position angle short wavelengths, where the Rayleigh scattering by small particles dominates, is then roughly consistent with a scattering region close to the Mira, while the large particles are presumably dominating at larger distances from the Mira, which may account for the difference between p.a. at $UB$ and $VRI$.

The polarization geometry of RX Pup can be compared with the geometry of its ionized nebula. There are two main directions for mass outflow distinguished in the nebula which are roughly perpendicular to each other (Corradi & Schwarz 2000): the previously known elongated optical/radio feature at p.a. $\sim 15^\circ$ with a velocity decreasing with distance from the central object, and a new EW compact component expanding at $\geq 80$ km/s, probably with a bipolar shape. The elongated structure would then be roughly perpendicular to the deduced binary axis, whereas the compact bipolar flow would be aligned with the binary axis.

The orientation of the binary axis will of course change with the binary motion. The shape (geometry) of the neutral region where the dust can be effectively formed, and so the scattering geometry, will also change with the hot component properties, for example with temperature and luminosity - which determine the number of ionizing photons available, and with wind efficiency - which influences the position of the shock front between the components. Thus, further studies involving both high resolution imaging techniques together with spectropolarimetry are necessary to reveal much more detailed information about the geometry of the circumstellar environment of RX Pup.

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