Astron. Astrophys. 355, 256–260 (2000)

ASTRONOMY
AND
ASTROPHYSICS

Research Note

The spectropolarimetric observations of three outburst objects, CI Camelopardalis, Nova Sagittarii 1998, and U Scorpii

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Received 17 September 1999 / Accepted 13 January 2000

Abstract. We carried out spectro-polarimetry of three outburst objects, CI Cam, Nova Sgr 1998, and U Sco. Although we were not able to detect the evidence of the intrinsic polarization for the former two stars, we succeeded in confirming the existence of intrinsic polarization for the last one, U Sco. U Sco showed de-polarization effect on emission lines. It also showed rapid variation of the continuum polarization. Its behavior resembles that observed for a classical nova, V1974 Cyg, although the time-scale of variation differs between two novae.

Key words: stars: novae, cataclysmic variables – stars: individual: U Sco – stars: individual: CI Cam – stars: individual: Nova Sgr – techniques: polarimetric

1. Introduction

Nova is a phenomenon in which huge energy ($\sim 10^{45}$ erg) and material ($\sim 10^{-4}$ $M_\odot$) are suddenly released. It is widely accepted that a nova eruption is triggered by the thermonuclear runaway on the surface of a compact degenerate star following mass transfer from a late type companion.

In many cases, the ejected material is considered to expand non-spherically and inhomogeneously even during the early stage of the outburst. To study such asymmetrically distributed circumstellar material, *spectropolarimetry* is a very useful method, because not only we can obtain information on the asymmetry itself from linear polarization, but also it permits separation between the line and continuum components, which easily enables us to estimate the foreground interstellar polarization. In addition, information on the wavelength dependence of continuum polarization is of great benefit on distinguishing the origin of the polarization. (e.g. we can estimate which of electrons or dust grains are the scattering matter.) However, few spectropolarimetric observations of novae have been carried out in the past (e.g. Bjorkman et al. 1994). We carried out spectropolarimetry of recent novae or nova like objects (CI Cam, Nova Sgr 1998, and U Sco). In this paper, we report the observational results and briefly discuss the intrinsic polarization for these objects.

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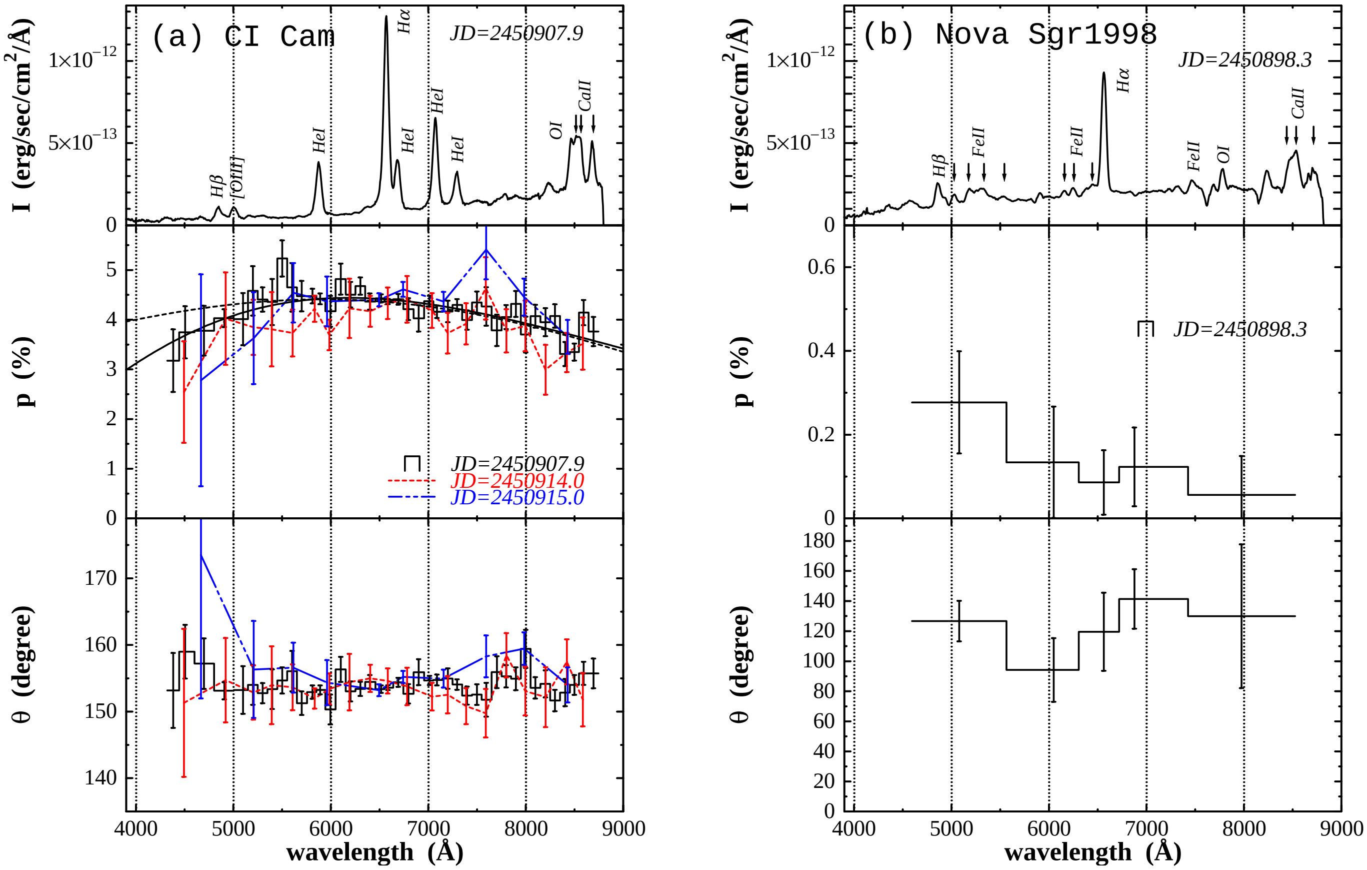
Table 1. The journal of observations: The third column shows the exposure time per a frame times the number of frames.

Star name	Date (JD-2450000)	Exp. time (sec)	Comments
CI Cam	1998 Apr.4 (0907.9)	50 s $\times$ 14	
	1998 Apr.10 (0914.0)	200 s $\times$ 14	
	1998 Apr.11 (0915.0)	200 s $\times$ 14	
Nova Sgr1998	1998 Mar.25 (0898.3)	200 s $\times$ 6	low S/N
U Sco	1999 Feb.25 (1235.3)	120 s $\times$ 12	
	1999 Feb.27 (1237.2)	150 s $\times$ 14	low S/N

2. Observations and reduction

We observed three outburst objects, CI Cam, Nova Sgr 1998, and U Sco, using the low resolution spectropolarimeter, HBS (see Kawabata et al. 1999), mounted on the 36 inch reflector at the Dodaira observatory. As for the observations and subsequent reduction procedures, we followed the standard method introduced by Kawabata et al. (1999). In observations, we used the D1 diaphragm (17” ϕ, projected on the sky), resulting in the spectral resolution of about 100 Å which is limited by the seeing size. In reduction, we binned the Stokes parameter spectra ($Q(\lambda)$ and $U(\lambda)$) to reduce the photon noise as far as possible. The resultant data quality is $\Delta P/P \leq 0.2$ typically. However, we cannot attain such qualities for some objects or in some wavelength regions due to the low S/N: $\Delta P/P \leq 0.4$ on Apr.10 and ≤ 0.75 on Apr.11 for the blue region (< 5000 Å) of CI Cam, respectively, non significant detection for Nova Sgr 1998, and $\Delta P/P \leq 0.8$ for U Sco on Feb.27. The polarization spectra are displayed in Fig. 1a–c.

The journal of observations is shown in Table 1.



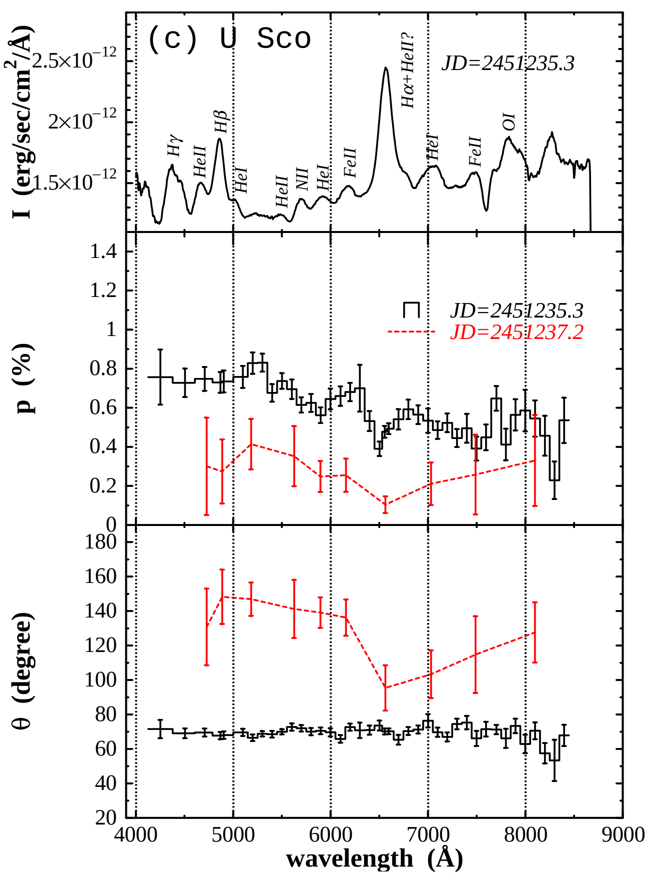


Fig. 1. The polarization spectra of **a** CI Cam, **b** Nova Sgr 1998, and **c** U Sco. Top panels (I) show the flux uncorrected for air-mass, middle panels (p) show the polarization degree, and bottom panels (θ) show the position angle. In the middle panel of Fig. 1a, the solid curve represents the best fitted solution with the Serkowski law (see text), while the dashed curve is the solution with the Wilking law for the interstellar polarization.

3. Results

3.1. CI Cam

CI Cam has been known as a binary system consisting of an OB and a late type star. IR observations suggest that there is circumstellar dust envelope (Allen 1973 and Bergner et al. 1995). On the other hand, CI Cam was also rediscovered as an X-ray transient object, XTE J0421+560, at the end of March 1998. The optical and radio flux reached their maximum 2 - 3 days after the X-ray maximum. The radio observations revealed that the spectral index was consistent with synchrotron radio emission (Hjellming et al. 1998a). An S-shaped twin radio-jet similar to the jet of SS433 was discovered about a week after the outburst (Hjellming et al. 1998b).

As displayed in Fig. 1a, CI Cam showed large polarization degree up to 4%. The feature of polarization suggests that interstellar polarization would be dominant, since (i) the position angle is almost constant ($\approx 152°$) throughout the optical range, and roughly consistent with the average position angle of nearby field stars ($137.6 \pm 9.9°$) as shown in Fig. 2 and Table 2, (ii) neither the polarization degree nor the position angle shows significant temporal variation during our observational run (Fig. 1a), when the optical flux was declining and the X-ray radiation was already silent (Frontera et al. 1998), (iii) there are no differences of polarization between the emission lines and the neighboring continuum (Fig. 1a), (iv) the contribution of synchrotron radiation to the optical flux, extrapolated from the radio flux published by Frontera et al. (1998), is < 0.5% of the total flux on Apr.4.

In order to estimate the contribution of the interstellar polarization, we carried out least-square fitting of Serkowski's empirical formula (Serkowski et al. 1975 and Wilking et al. 1980) to all data,

$$p = p_{\max} \exp\left[-K \ln^2 \left(\lambda_{\max}/\lambda\right)\right], \qquad (1)$$

where $\lambda_{\max}$ is the wavelength at maximum polarization ($= p_{\max}$) and K is a constant parameter. We assume that $\lambda_{\max}$, $p_{\max}$, and K are free parameters independent one another. The observed data are relatively well fitted with this equation (see Fig. 1a, reduced $\chi^2 = 0.97$). The best fitted values are $p_{\max} = 4.44 \pm 0.03$%, $\lambda_{\max} = 6190 \pm 104$ Å, and $K = 1.86 \pm 0.27$. We should note that the K value is relatively larger than those of typical interstellar polarization in any models (e.g. Serkowski et al. 1975, Wilking et al. 1982, and Whittet et al. 1992). Large K values were reported in Nova V705 Cas, which were attributed to the light scattered by a dusty circumstellar envelope (Kawabata et al. 1996). To examine the difference of polarization spectra from that of the typical interstellar polarization, we reduced three free parameters of Eq. (1) to two ($p_{\max}$ and $\lambda_{\max}$) with Wilking law (Wilking et al. 1982), $K = -0.10 + 1.84\lambda_{\max}$ (μm), which well reproduces the interstellar polarization in spite of only two free parameters. The best fitted values are $p_{\max} = 4.41 \pm 0.04$% and $\lambda_{\max} = 5915 \pm 170$ Å. The reduced χ^2 (= 1.05) is slightly larger, because, at a glance, the fitted curve dose not well reproduce data points (or the Serkowski curve with three parameters) in the blue region (Fig. 1a). This failure to fit with Wilking law, equivalent with large K value, might suggest the existence of an intrinsic component of the polarization. However, the value of $\chi^2 = 1.05$ indicates that the fitted curve statistically agrees with data points at 5% significant level. Therefore, we conclude that the optical polarization in outburst phase of CI Cam is primarily interstellar origin.

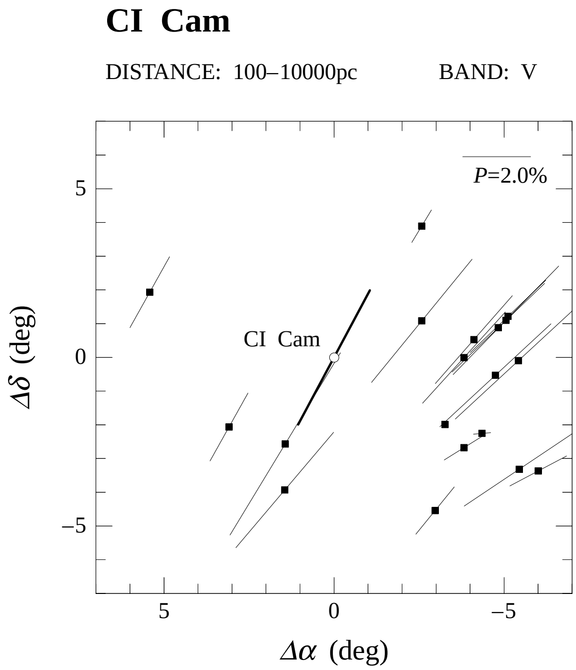


Fig. 2. The interstellar polarization of the field stars around CI Cam: The length of bars shows the polarization degree, while the direction is the position angle. The polarization of CI Cam is the V-band value on Apr.4 (JD=2450907.9). We can see that the position angle of CI Cam is fairly consistent with those of the field stars. The interstellar polarization of the field stars around other two novae, Nova Sgr 1998 and U Sco, are summarized in Table 2.

3.2. Nova Sgr 1998

Nova Sgr 1998 was discovered by Liller (1998). It brightened up to $V = 7.8$ mag at Mar.25 1998, and then rapidly faded away. It can be classified as a fast nova since $t_3 \simeq 40$ days. It is also classified as Fe II class nova, because it showed weak P Cygni profile on the Balmer lines and Fe II lines (Williams 1992 and della Valle et al. 1998).

Nova Sgr 1998 had very small polarization ($p \simeq 0.2$%, Fig. 1b). It is hard to derive any reliable wavelength dependence from such small polarization. The position angles of nearby field stars do not systematically align (Table 2). Therefore, we cannot employ the field-star method to estimate the interstellar polarization. At any rate, we could not be confident of the existence of intrinsic polarization of Nova Sgr 1998.

Table 2. Comparison between the interstellar polarization estimated with the field-star method and the observed polarization: $\theta_{\rm V}$ is the position angle of each object in V-band. $\theta_{\rm ave}$ is the averaged position angle of the field stars, weighted with their polarization degrees. All polarization data of field stars are extracted from the interstellar polarization library by Hirata et al. (1999). For Nova Sgr 1998, the polarization pattern of nearby stars is rather complicated. Thus, the $\theta_{\rm ave}$ is not reliable for the interstellar polarization. There are few sample stars for U Sco.

Object name	$\theta_{\rm V}$ (date)	$\theta_{\rm ave}$	Field radius (arcdeg)	Number of sample stars	Distance to stars (kpc)
CI Cam	$152.1°$ (0907.9)	$137.6 \pm 9.9°$	5.0	21	0.1 - 10
Nova Sgr 1998	$129.3°$ (0898.3)	$3.8 \pm 16.5°$	10.0	32	2 - 10
U Sco	$69.1°$ (1235.3)	$36.5 \pm 33.0°$	10.0	6	0.1 - 15

3.3. U Sco

U Sco is known as one of the five recurrent novae (Vogt 1989). The typical light curves which U Sco has shown also classify it as a very fast nova. Many authors mentioned that the outburst of U Sco would be triggered by a thermonuclear runaway in the same manner as the widely accepted model for classical novae (Webbink et al. 1987, Starrfield et al. 1988, Duschl et al. 1990, and Kato 1990).

As shown in Fig. 1c, the observed polarization drastically varied with time, which is evidence for the existence of an intrinsic component. The polarization degree decreased by about 0.5% over the optical region within only two days. The spectrum of the polarization degree does not trace that of the interstellar polarization (cf. Eq. (1)). At the strongest emission line (Hα + He II?), the polarization degree is small compared with those of neighboring continuum, which suggests that the scattering material is located within (and/or nearer to the pseudo-photosphere than) the emission line region. The Hβ, the second strongest emission line, does not show the de-polarization. This is because the Hα region is more extended to the outside than the Hβ region, since the population of the H-atom with higher energetic level is more larger in the inner region than in the outer region. For the position angle, while the wavelength dependence seems to be flat on the first night (JD=2451235.3), it showed a rather complicated structure on the second night (JD=2451237.2, 2.5 days after the outburst). Those of the blue (< 6000 Å) and the red continuum (> 7000 Å) rotated by about $70°$ and $50°$, respectively, during two days. On the other hand, the rotation angle was relatively small at the strongest emission line, Hα. This indicates that the polarization observed on the first night was dominated by the interstellar polarization, and that the intrinsic component became significant on the second night. The position angle obtained on the first night is roughly consistent with the averaged position angle of the field stars, which supports our idea, although the available sample of them is rather few (see Table 2).

Assuming the polarization on the first night is the interstellar component wholly, we can estimate the intrinsic component from the polarization on the second night by the following equations (Andersson & Wannier 1997),

$$p_{\rm 2nd} \cos 2\theta_{\rm 2nd} \;=\; p_* \cos 2\theta_* + p_{\rm ISP} \cos 2\theta_{\rm ISP}, \qquad (2)$$

$$p_{\rm 2nd} \sin 2\theta_{\rm 2nd} \;=\; p_* \sin 2\theta_* + p_{\rm ISP} \sin 2\theta_{\rm ISP}, \qquad (3)$$

where the suffix '2nd', '$*$', and 'ISP' represent the second night, the intrinsic component, and the interstellar component, respectively. Since $(p_{\rm 2nd}, \theta_{\rm 2nd}) = (0.30\ \%, 140.0°)$ and $(p_{\rm ISP}, \theta_{\rm ISP}) = (0.70\ \%, 69.1°)$ at the V-band, we obtained the intrinsic polarization $(p_*, \theta_*) = (0.95 \pm 0.09\ \%, 153.5 \pm 2.7°)$.

We discuss the origin of such intrinsic polarization as follow. The de-polarization in the emission lines in U Sco reveals that the scattering matter lies inside of the emission line region. We consider that free electrons in the circumstellar plasma are the most plausible candidate for the scatterer. Although scattering by dust grains is one of the candidates, it is unlikely that grains can condensate in the early stage of nova evolution (= only a few days after the outburst). We can estimate the initial dust forming time ($= t_{\rm d}$) by using Gallagher's (1977) equation,

$$t_{\rm d} = \frac{2}{T_{\rm d}} \left(\frac{L_{\rm CL}}{4\pi\sigma}\right)^{1/2} \frac{1}{v_{\rm exp}}. \qquad (4)$$

Setting the condensation temperature of dust $T_{\rm d} = 2000$ K, the expanding velocity $v_{\rm exp} = 5000$ km s^{-1} (Niedzielski et al. 1999), and the luminosity during the constant luminosity phase $L_{\rm CL} = 6 \times 10^4\ {\rm L}_\odot$ (typical value for a very fast nova, Gallagher 1977), we get $t_{\rm d} = 6.6$ days. The dust model can hardly explain the polarization variation observed 2.5 days after the outburst.

Some authors have mentioned that electron scattering is the dominant mechanism for the polarization in the early stage for some novae. Bjorkman et al. (1994) suggested that the large rotation of the position angle of the intrinsic polarization in V1974 Cyg was due to geometrical evolution of the ionized circumstellar ejecta. They explained that once it entered the nebular phase, the two stars which had been hidden by the pseudo-photosphere would appear and the beam from the central system could escape from the inner region. Since this beam could be scattered by the optically thin envelope along (or perpendicular to) the binary axis, which also appeared after the transition phase, the polarization alternative to that of the scattered light of the pseudo-photosphere would be newly produced.

This change of the position angle in V1974 Cyg had occurred about 80 days after the outburst. However, for U Sco, the time-scale for change is much shorter. The large difference of the time-scale between the two novae might be concerned with the difference of the speed class. If we adapt Bjorkman and his collaborator's picture and recall that U Sco is a eclipsing binary system (Schaefer 1990), we can estimate the position angle projected on the sky of the orbital axis from the position angle of the intrinsic polarization above obtained. Assuming that (i) the polarization on the second night is due to intrinsic component and (ii) the pseudo-photosphere had disappeared between the first night and the second night, we obtain two solutions for the position angle of orbital axis, $\simeq 65^\circ$ (for the scattering envelope along the orbital axis) or $\simeq 155^\circ$ (for perpendicular to the orbital axis).

Spectropolarimetry of novae and nova like objects is very useful for explicating the nature of the ejecta, in particular the spatial distribution and components of the medium, but as yet there have been few samples. In order to arrive at that goal early, additional spectropolarimetric observations of these objects are necessary. For this propose, we have to construct equipment with sufficient flexibility and a network system notifying information immediately for unpredictable objects.

Acknowledgements. We would like to thank M.Kondoh, N.Hirakata, K.Saijo, K.Yoshioka, and H.Sato for helping our observations. We are indebted to the VSNET database and VSOLJ database for the light curve of novae.

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