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LETTER

Letter to the Editor

Phase variability in the optical polarization of GRO J1655–40

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Abstract. We present the results of the new optical polarimetric observations of the superluminal source GRO J1655–40, carried out in July 1997, with the multichannel photopolarimeter of the Torino Observatory, using the 2.15-m telescope of Complejo Astronomico El Leoncito (Argentina). The observed amount of polarization shows (mainly in the V and I bands) oscillations which are consistent with the orbital period of the system. This gives information about physical and geometrical properties of the binary system and confirms that the optical continuum is intrinsically polarized. The origin of the polarized flux is likely to be related to electron scattering of photons from the accretion disk.

Key words: polarization – stars: individual: GRO J1655–40 – stars: novae, cataclysmic variables

1. Introduction

The microquasar GRO J1655–40 (Nova Scorpii) has been one of the most studied celestial objects in these last years both from the observational and the theoretical point of view. It shows peculiar behaviour at all frequencies, from radio to hard X-rays: in particular, thermal and non thermal emission and large amplitude variability on short time scales. However the most important feature, shared only with GRS 1915+105, is the ejection of radio emitting blobs with superluminal motion. This phenomenology is interpreted as due to the activity of an accretion disk surrounding a black hole of a few solar masses in a binary system, with accreting material feeding the disk coming from a companion star via Roche Lobe overflow (for a review of the main properties of Nova Scorpii and GRS 1915+105 see Hjellming & Rupen 1995 and Mirabel & Rodriguez 1995).

The observation of Bailyn et al. (1995b, V band) can provide useful informations on the optical behaviour of the microquasar when it is active:
i) the source is about 0.7–0.8 magnitude brighter in V with respect to the quiescent phase ($16.3 \leq V \leq 16.8$);
ii) there is an exchange of the locations of the two minima during the orbital period. In the bright state the primary minimum is at the orbital phase $\phi = 0.0$, and is due to the eclipse of the accretion disk by the secondary star.
iii) the phases of minima do not line up properly with the spectroscopic phase (the difference in phase is as large as 0.05). This suggests that during the active status the disk is probably asymmetric.

Further informations on the structure of GRO J1655–40 can be collected from optical polarimetric observations. In July 1996, during a phase of high X-ray and radio activity begun in May 1996, the optical flux from the source was polarized by an amount of $2.5 \div 4\%$ in the VRI bands, with the polarization direction nearly parallel to the accretion disk plane, assumed perpendicular to the jet axis (Scaltriti et al. 1997).

New optical polarimetric observations of GRO J1655–40 were performed at the 2.15-m telescope of Complejo Astronomico El Leoncito (Argentina) with the five channel photopolarimeter of Torino Observatory (Scaltriti et al. 1989) in the period July 1–8, 1997, when the X-ray activity was high (flux ~ 1 Crab, 2–10 keV) but lower than in July 1996. With respect to the 1996 observations we have followed in more detail the behaviour of the polarization parameters in different bands with the orbital period.

2. Observations

The observed magnitudes in the three bands VRI, the amount of polarization P, the position angle θ and the orbital phase are reported in Table 1 (the low flux in the U and B bands does not allow a useful polarimetric analysis). A single determination of the polarization parameters derives from rotations of 180° of the $\lambda/2$ plate over steps of $22.5°$. Each step lasts 10 s, and the whole cycle is repeated several times, for a total run of ≈ 45 minutes. Therefore each value of the polarization parameters

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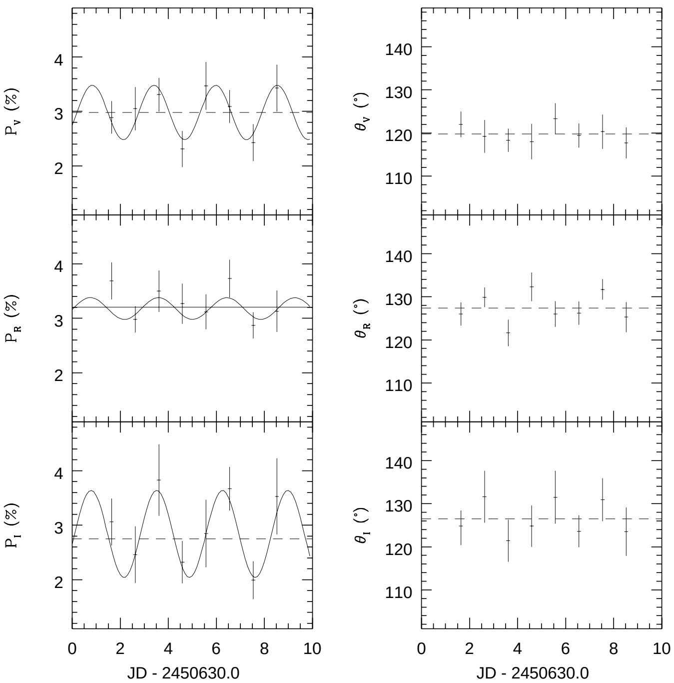

Fig. 1. Plot of the observed fraction of polarization P (left panel) and of the position angle θ (right panel) as function of the time (JD - 2450630.0) in the three bands V, R and I (from top to bottom). The dotted lines are the average values. The best fits to a sinusoidal curve are overplotted to the data of P by fixing the oscillation amplitudes $P_{1,V} = 0.5$%, $P_{1,R} = 0.2$% and $P_{1,I} = 0.8$%, respectively

has been obtained over observational times corresponding to a fraction ≈ 0.015 of the orbital period.

Considering our photometric data, we can only infer that the source is in the range of $15.1 \leq V \leq 15.6$, about a magnitude brighter than the values obtained during the active phase in March 1995 and roughly 0.7 magnitudes fainter than the brightest value ever observed (Bailyn et al. 1995a). At JD 2450634 and 2450638 the sky conditions did not allow to derive reliable photometry.

3. Results

The temporal behaviour of P and θ in the three bands is plotted in Fig. 1. To verify that the observed fluctuations in P are real we have performed a χ^2 test assuming for the observed polarization fraction a sinusoidal fluctuation overlapped to a constant component: $P = \hat{P} + P_1 \sin(2\pi/T + \psi)$. In this expression $\hat{P}$ is the (weighted) average value obtained in the three bands, $\hat{P}_V = 2.98\%$, $\hat{P}_R = 3.18\%$, $\hat{P}_I = 2.84\%$, while P_1, T and ψ are the amplitude, the period (in days) and the phase of the oscillating component, respectively. We remind that the orbital period of the system is $T \simeq 2.62$ days (van der Hooft et al. 1998) and from our first observation we obtain $\psi = -0.401$. In our tests we have assumed as parameters of the fit the amplitude and the period of the oscillations. As only 8 data points are available we have carried out the tests by fixing for each fit one of the two parameters (the reported errors are at 68% confidence level for 7 degrees of freedom).

1) For $P_1 = 0$ (i.e. the hypothesis of constant P) the possibility that the observed curve depends only on a statistical fluctuation is $\lesssim$16% (V), $\lesssim$32% (R) and $\lesssim$4% (I). Fixing T at the orbital period we have found for the amplitude of the oscillations $P_{1,V} = 0.5 \pm 0.2$ ($\chi^2 = 1.7$), $P_{1,R} = 0.2 \pm 0.2$ ($\chi^2 = 6.6$) and $P_{1,I} = 0.8 \pm 0.2$ ($\chi^2 = 3.6$). The uncertainties are quite large, however we can see that at 99% confidence we have as lower limits for the amplitudes $P_{1,V} \gtrsim 0.1$ and $P_{1,I} \gtrsim 0.2$.

2) To estimate the oscillating period we have fixed P_1 at the best values deduced in the previous fits. We have found $T_V = 2.6 \pm 0.1$ ($\chi^2 = 1.4$), $T_R = 2.8 \pm 0.2$ ($\chi^2 = 5.0$) and $T_I = 2.7 \pm 0.1$ days ($\chi^2 = 2.1$). Acceptable values are also obtained for the first upper 3–4 harmonics, while no good fit is found up to $T = 10$ days. These values are consistent, within 1σ, with the orbital period.

3) The possible intrinsic differences of the temporal curves of P in the three bands have been checked, assuming as the best result the fit deduced in the I band. We have found that polarization data in V and R can be consistent with the best fit in I at $\lesssim$20% and $\lesssim 4 \times 10^{-3}$ of probability, respectively.

Concerning the temporal behaviour of the position angle, we found that the observed variations of θ around its average values ($\hat{\theta}_V = 119.8°$, $\hat{\theta}_R = 127.4°$, $\hat{\theta}_I = 126.5°$) can be ascribed to statistical fluctuations with probability $\lesssim$90% (V), $\lesssim$13% (R) and $\lesssim$75% (I). We have further verified that the possible periodicity in the R band has a period of 1.6 ± 0.1 days.

The results of these fits to the P data have been overplotted to the observed data in Fig. 1. From the quite accurate determination of the period we can reasonably assume that the observed fluctuations in the V and I bands are real and related to the orbital period of the system. We remark that the low values of the χ^2 imply that our measurements are affected by systematic errors higher than expected from statistical uncertainties alone. The estimate of the amplitude of oscillations is quite poor, and the value in the R band could be assumed as an upper limit. It must be pointed out also that evidence of polarization oscillations has been found in both the I and V bands, but in I the object is brighter by $\approx 1.5 \div 2$ magnitudes.

4. Discussion

Concerning the photometry, the most important implications of our data, when compared with previous observations, is that GRO J1655-40 is quite bright at optical wavelengths in spite of its moderate X-ray activity. However the light curve is not detailed enough for a reasonable comparison with previous observations, when the source was in different activity phases.

In order to gain informations about the physical and the geometrical properties of the binary system from the temporal fluctuations of the polarization parameters, we have plotted in Fig. 2 the polarization fraction vs the photometric phase.

On the basis of the discussion in the previous Section, the observed fluctuations in the amount of polarization seem to be

Table 1. (the errors are at 1σ level)

FILTER	MAG	P(%)	$\theta(^\circ)$	ϕ	JD
V	15.57±0.03	2.89±0.30	122.0±3.0		
R	14.92±0.03	3.69±0.34	126.0±2.7	0.562	2450631.6405
I	14.03±0.03	3.06±0.43	124.8±4.0		
V	15.51±0.06	3.05±0.40	119.2±3.8		
R	14.88±0.04	2.98±0.24	129.9±2.3	0.937	2450632.6237
I	13.96±0.07	2.46±0.52	131.6±6.0		
V	15.35±0.04	3.31±0.31	118.3±2.7		
R	14.81±0.03	3.50±0.38	121.6±3.1	0.312	2450633.6068
I	13.78±0.05	3.83±0.66	121.4±4.9		
V	–	2.31±0.33	118.0±4.1		
R	–	3.27±0.37	132.3±3.3	0.687	2450634.5899
I	–	2.32±0.39	124.8±4.8		
V	15.63±0.05	3.47±0.44	123.3±3.6		
R	15.24±0.07	3.12±0.32	126.0±3.0	0.062	2450635.5731
I	14.29±0.05	2.85±0.62	131.5±6.1		
V	15.50±0.04	3.09±0.30	119.4±2.8		
R	15.23±0.04	3.73±0.35	126.2±2.7	0.437	2450636.5562
I	14.25±0.06	3.67±0.47	123.6±3.7		
V	15.12±0.05	2.43±0.34	120.3±4.0		
R	14.87±0.05	2.87±0.24	131.7±2.4	0.812	2450637.5393
I	13.85±0.05	1.99±0.35	130.9±5.0		
V	–	3.43±0.43	117.7±3.6		
R	–	3.13±0.38	125.3±3.5	0.187	2450638.5224
I	–	3.53±0.70	123.5±5.6		

related to the eclipses in the binary system. In this case, the modulation of P can be due both to the occultation of the region from which the polarized light originates and to a variation of the non polarized flux due to the eclipses in the system. One can then deduce that both the polarization region and the covering medium must be extended, respectively because of the long fall and rise time and of the smooth modulations in the amount of polarization.

The most evident feature in the shapes of the polarization curves in all the VRI bands is the minimum of P at $\phi \simeq 0.7 \div 0.8$, when the accretion disk and the secondary star are roughly in quadrature. Note also the lack of a similar minimum in the symmetric quadrature phase $\phi \sim 0.25$; this may suggest that the system (and particularly the accretion disk) is asymmetric. It is also worth noticing that the minimum of the polarized amount, in the VRI bands, occurs nearly at the same orbital phase of the X-ray dips (Ueda et al. 1998, Kuulkers et al. 1998). Therefore it could be related either to thickening of the disk rim, where the stream from the companion hits the accretion disk (Parmar & White 1988), or to the remnant stream, which propagates inward above and below the disk after the impact with the disk rim (Frank et al. 1987).

Another peculiar feature of $P(\phi)$ is that the maximum of polarized fraction seems to lie in the phases $\approx 0 \div 0.5$, depending on the band. Let us assume that during the active state the accretion disk becomes hotter than the companion star (as suggested in Bailyn et al. 1995b) and that the region of emission of polarized photons is partially obscured in the eclipse ($\phi \approx 0$). In the I band the contribution of (unpolarized) photons from the companion star to the total flux are prevailing, then we can expect the maximum of polarization at $\phi \approx 0.5$ when the disk is fully visible and the companion star partially obscured. This effect is further enhanced if the inner hemisphere of the secondary (i.e. the one facing the compact object) is heated up by the X-ray emission from the disk.

In the V band the behaviour is more complicated, as the diluting effect of the flux from the companion should be reduced. Then at $\phi \approx 0$ the high energy photons from the disk (polarized and unpolarized) are partially obscured, while all the disk is unveiled for $\phi \approx 0.5$. We could justify the observed oscillations of P in V by assuming that the region of emission of polarized flux reduces by increasing the photon energy, such that when the disk is eclipsed only its unpolarized photons are obscured. Furthermore at $\phi \approx 0.5$ the polarization fraction could be reduced by the emission of the heated up hemisphere of the companion star. In such a case the maximum of P should be shifted to $\phi \approx 0$: this seems to be the trend when comparing the V and I curved in Fig. 2. However our data do not allow a strong support for this possibility. For intermediate wavelengths these two different effects may compensate, leading to a much less

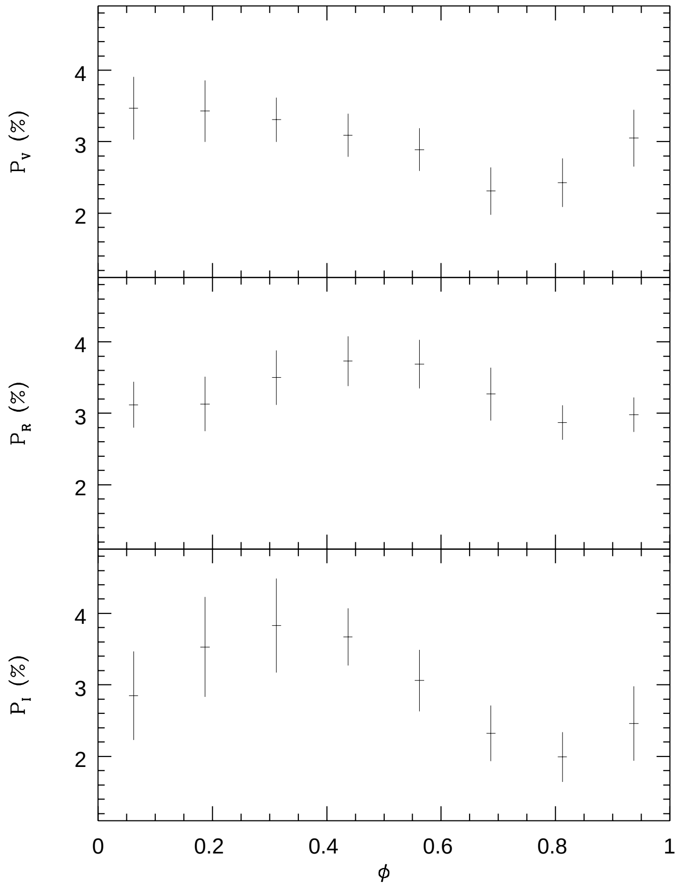

Fig. 2. Plot of P vs the photometric phase ϕ in the three bands V, R and I (from top to bottom)

evident oscillations of the polarized flux, as observed in the R band.

In the previous paper (Scaltriti et al. 1997), we were not able to say whether the origin of the polarized optical continuum was due to a nonthermal emission process (synchrotron emission from the relativistic plasma inside the jet) or to electron scattering. If the previous interpretations on the P oscillations are reasonable, we can deduce now informations on the physical mechanism providing the polarized photons and on the geometry and location of the region where polarized photons originate. The presence of smooth eclipse-like modulations in the polarization curve implies that the polarization region must be rather extended and lie, at least partially, near the inner part of the accretion disk. The same argument excludes, as a possible origin of the polarized optical continuum, both the jet far away from the accretion disk, that is never eclipsed, and the jet near the compact object, that cannot have a large spatial extent. Therefore we conclude that the synchrotron emission from the jet cannot be the physical mechanism originating the observed polarized radiation. The most likely explanation is the electron scattering by plasma above the accretion disk. It must be noticed that the presence of a highly ionized plasma structure, similar to the one argued by our polarimetric observations, has been recently confirmed by ASCA observations (Ueda et al. 1998).

5. Summary

We have presented the results on new photopolarimetric observations of GRO J1655–40, carried out in July 1997, when the X-ray activity of the source was still high but constantly decaying. These are the main conclusions:

- With respect to July 1996 the source was brighter in optical ($15.1 \leq V \leq 15.6$ versus $V \sim 16.2$), while the X-ray flux (2–10 keV) was ≈ 3 times dimmer.
- The observed fraction of polarization ($\approx 2.8 \div 3.2$%) shows small amplitude oscillations in the V and I bands with a period consistent with the orbital one.
- The curve $P(\phi)$ shows in all bands a minimum at $\phi \simeq 0.7 \div 0.8$, interpreted as an asymmetric structure in the accretion disk. The shape of $P(\phi)$ in VRI for $0 \lesssim \phi \lesssim 0.5$, is probably related to the diluting effect of the unpolarized flux from both the star and the disk, and to the partial eclipse of the region where the polarization photons originate.
- The smoothness in the polarimetric modulations suggests that the polarization region is rather extended and close to the inner accretion disk. Electron scattering from this zone seems to be the likely origin of the polarized photons.

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