NEW OBSERVATIONS OF THE OLD MAGNETIC NOVA GQ MUSCAE

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Abstract. Photometric observations of GQ Mus performed between 1992 and 2011 are reported. We find that the total amplitude of the orbital modulation of its brightness decreased from ~0.9 mag in 1992 to ~0.2 mag in 2010, becoming comparable to the amplitude of chaotic flickering on a time scale of several minutes. Optical spectra obtained in 2001 and 2012 indicate continuing activity of GQ Mus. The spectra show broad emission lines of He II and H I typical for magnetic cataclysmic variables. The nova was found to be an UV-bright object in 2001 and 2012. We also show that the orbital period of GQ Mus has been constant between 1989 and 2010–2011.

Key words: stars: individual: GQ Mus – novae – cataclysmic variables

1. INTRODUCTION

The cataclysmic variable GQ Muscae (Nova Muscae 1983) is a classical nova. It was discovered by W. Liller on 1983 January 18 (Shylaja 1983; Liller & Overbeek 1983). At the moment of discovery its brightness was estimated at 7.2 mag. The post-outburst optical light curve of GQ Mus was unusual: after an early decline lasting for about four months its brightness remained approximately constant for the next five months (Krautter et al. 1984). Duerbeck (1987) classified it as a moderately fast nova with $t_3 = 45$ d. With a pre-outburst magnitude of $V \geq 21$ (Krautter et al. 1984) GQ Mus belongs to a few known novae whose outburst amplitude approaches or even exceeds 14 mag.

Early spectra of GQ Mus were characterized by broad and strong H I and He I emission lines. Lines of Fe II, Ti II and N III were also visible, and they indicated a fast expansion of the ejected envelope (Charles 1983; Whitelock et al. 1983). The spectra obtained between 1984 and 1994 showed lines of highly ionized atoms, indicating a very high temperature of the central source of $2.65 \times 10^5$ K (Diaz et al. 1995; Morisset & Pequignot 1996).

Photometric observations obtained in 1988 by Diaz & Steiner (1989) revealed
the brightness modulation with a period of 85.5 min. The light curve was asymmetrical, with the full range reaching 1 mag in the V-band. Further photometric and spectroscopic monitoring allowed to classify GQ Mus as a magnetic cataclysmic variable (Diaz & Steiner 1990, 1994). Radial velocities measured from the strong emission lines of He II $\lambda$4686, O IV $\lambda$3411 and N III $\lambda$5270 could be phased with the photometric period. The natural interpretation is that the 85.5 min periodicity corresponds to the orbital period of the system.

GQ Mus was the first classical nova with X-ray emission detected during an outburst (Ögelman et al. 1984). It remained in the active state for several years longer than predicted – supersoft X-ray emission persisted in 1992 (Ögelman et al. 1993). Later observations conducted in 1993 showed that the X-ray flux had decreased by a factor of 100 within one year (Shanley et al. 1994), indicating the extinction of the supersoft X-ray source.

These unusual properties of GQ Mus prompted us to embark on an occasional photometric monitoring of this object between 1992 and 2011. In the present paper we report the results of those observations. We also present two optical spectra obtained in 2001 and 2012. The next section summarizes the observations, data reduction and calibrations. In Section 3 we discuss the main results, and a brief summary of the paper is given in Section 4.

2. OBSERVATIONS, DATA REDUCTION AND CALIBRATION

Photometric observations of GQ Mus were made in the period 1992–2011 with the 1.0 m Swope and 2.5 m du Pont telescopes at the Las Campanas Observatory.

Fig. 1. Light curve of GQ Mus for the period 1992–2011.
The TEK2 and SITE3 CCD cameras were used on the Swope telescope, and the TEK5 and SITE2K cameras on the du Pont telescope. The log of the observations is given in Table 1. The variable was observed on 28 nights, yielding a total of 1080 $V$-band frames and 25 $B$-band frames. In 2001 we also obtained two frames with SITE3/Swope in the $U$-band.

Profile photometry was extracted using the Daophot/Allstar programs (Stetson 1987, 1990). The data from SITE3 were additionally reduced with the image subtraction code ISIS (Alard & Lupton 1998; Alard 2000). Measurements were transformed to the standard $UBV$ system based on observations of ten standard stars from two Landolt fields (Landolt 1992) performed on 2001 June 17/18. The standard stars were observed at air-masses of 1.15 and 1.20 while GQ Mus was observed at an air mass of 1.27. Assuming average extinction coefficients for Las Campanas, we obtained for GQ Mus $V = 18.65 \pm 0.02$ mag, $B-V = 0.27 \pm 0.02$ mag and $U-B = 0.78 \pm 0.03$ mag at HJD = 2452078.48. The data from the remaining cameras were transformed to the standard $BV$ system based on local standards observed with SITE3. For most of the differential $V$ photometry the accuracy of

Fig. 2. Phased light curves of GQ Mus in $V$ for the seasons 1992, 2002 and 2010–2011.
Fig. 3. Color-magnitude diagrams for the 3×5 arcmin² field centered on GQ Mus. Positions of the variable are marked with triangles, with $V = \sim 18.5$ mag corresponding to the season 2001, and $V = \sim 19.0$ mag to the season 2010.

Table 1. Summary of photometric observations of GQ Mus.

| Detector | Season | No. of Frames | Ave. exp. time in $V$ [s] | <Seeing> [arcsec] |
|----------|--------|---------------|--------------------------|-----------------|
| TEK2     | 1992   | 4 165         | 185                      | 1.5             |
| SITe3    | 1997   | 3 21          | 122                      | 1.3             |
|          | 2000   | 1 21          | 300                      | 3.0             |
|          | 2001   | 3 43          | 2 300                    | 1.5             |
|          | 2002   | 6 173         | 300                      | 1.8             |
| TEK5     | 2008   | 1 5           | 60                       | 1.5             |
| SITe2k   | 2010   | 8 395         | 19 70                    | 1.2             |
|          | 2011   | 2 257         | 4 60                     | 1.5             |

individual measurements ranges from 0.01 to 0.02 mag.

A medium resolution spectrum of the nova was obtained with the B&G spectrograph mounted on the Magellan Baade telescope. A 20 min exposure centered on 23:37 UT was made on 2001 June 18. The spectrum covered the range 3773–4490 Å at a resolution of 2800, and the average signal to noise ratio was of about 8. The second medium resolution spectrum of GQ Mus was obtained on 2012 April 1 with the South African Large Telescope. The RS spectrograph was used with the PC09000 grating and a 1.5 arcsec slit, providing a resolution of $R = 800$. Two 5 min exposures were centered on 00:38 UT. The combined spectrum has a signal to noise ratio of 2.3 and 2.8 at $H\beta$ and $H\alpha$, respectively. The reduced and flux-calibrated spectrum covers the range 3800–6575 Å with 60 Å wide gaps at 4530 Å and 5590 Å.
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3. RESULTS

In Figure 1 we present a schematic $V$ light curve of GQ Mus based on the data collected between 1992 and 2011. In that period the average luminosity of the nova dropped from $<V> = 17.87$ mag to $<V> = 19.01$ mag. Moreover, after 1992 the amplitude of the periodic variability has significantly decreased. It is possible that around 2009 the luminosity of the nova stabilized, as no systematic change of $<V>$ was observed during the subsequent two years. Note that in 2010-2011 the nova was still brighter than in its pre-outburst stage by 2 mag at least.

We have analyzed the light curves of GQ Mus for periodicity. For three seasons the amount of data was sufficient to establish the period with a high accuracy. We obtained $P = 0.05936538(\pm 8)$ d, $P = 0.0593640(\pm 2)$ d and $P = 0.05936553(\pm 4)$ d for the years 1992, 2002 and 2010-2011, respectively, where the errors are 1σ uncertainties of the last significant digit. Diaz & Steiner (1994) have obtained $P = 0.0593650(\pm 1)$ d for 1989–1990. The combined measurements indicate that the orbital period of GQ Mus was constant between 1989 and 2011 at a level of $dP/P \leq 1.7 \times 10^{-6}$. Phased light curves for 1992, 2002 and 2010-2011 are presented in Figure 2. The shape of the 1992 curve is generally similar to that obtained by Diaz & Steiner (1994) for the period 1989–1990. However, in 1992 the ascending branch was less steep, and the bump on the descending branch was less pronounced. The light curves for 2002 and 2010–2011 have an amplitude of only $\sim 0.1$ mag, and are noisy due to flickering on a time scale of a few minutes. The light curve for 1994 (Diaz et al. 1995) showed a significantly reduced amplitude in comparison with those for the 1989–1990 and 1992 seasons. Apparently the orbital

Fig. 4. The spectrum of GQ Mus of 2001 June 18 smoothed with a 7-pixel moving box.
modulation has weakened with time, becoming comparable to the amplitude of flickering in the 2010–2011 season.

With the galactic coordinates \( l = 297.2 \) deg and \( b = -5.0 \) deg, the nova resides in a rather crowded stellar field. For a heliocentric distance of 3.2 – 4.8 kpc (Diaz & Steiner 1994) it is located 280–420 pc above the galactic disk, so that it must be either a thick disk or a halo object. Figure 3 shows \( V/(B - V) \) and \( V/(U - B) \) color-magnitude diagrams (CMD) of the 3 \( \times \) 5 arcmin\(^2\) field containing GQ Mus. The nova is the bluest object on both CMDs, and the only UV-bright star in the analyzed field. While the \( V \) magnitude has increased by about 0.4 mag between 2001 and 2010, the object became redder by just 0.06 mag.

Figure 4 shows the spectrum taken in 2001 June, smoothed with a 7-pixel moving box. While smoothing reduces the resolution, it makes the broad Balmer emission lines better visible. Such broad Balmer lines have been observed in several polars and intermediate polars in an active state (Rosen et al. 1993; Pirola et al. 2008; Thomas et al. 2012). The spectrum obtained with the SALT telescope in 2012 April 1, smoothed with a 9-pixel moving box, is presented in Figure 5. It was flux calibrated and then normalized at 5500 \( \AA \). Balmer lines together with \( \text{He II} \lambda 4686 \) and \( \text{N III} \lambda 4650 \) are seen in emission, with \( \text{H}\alpha \) being particularly strong. The spectrum still exhibited signatures, typical for magnetic cataclysmic variables, as in 2012. Moreover, the spectrum implies a very blue color for the nova, Since no correction for interstellar reddening has been done, so that GQ Mus was even brighter in the ultraviolet than the slope of the spectrum suggests.
4. CONCLUSIONS

Almost three decades after the outburst of GQ Mus the object was still brighter than in its pre-outburst stage by 2 mag at least. Its light curve exhibited orbital modulation with a shape typical for magnetic CVs. Both in 2001 and 2012 the nova was bright in the ultraviolet. The spectra obtained in 2001 and 2012 show broad emission lines of H and He, typical for polars. We found no evidence for the period changes between 1989 and 2011 with an upper limit of \(\frac{dP}{P} \leq 1.7 \times 10^{-6}\).

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