RECOVERY OF THE X-RAY TRANSIENT QX NORMAE (=X1608 – 52) IN OUTBURST AND QUIESCENCE

Stefanie Wachter

Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195-1580; wachter@astro.washington.edu

Received 1996 December 11; accepted 1997 March 24

ABSTRACT

We present optical and near-IR observations of QX Nor, the counterpart to the recurrent soft X-ray transient X1608 – 52, after its reappearance following the X-ray outburst in 1996 February. The object has been seen only once before, during an X-ray outburst in 1977. Data from 3 to 5 months after the outburst show the counterpart at a mean magnitude of R = 20.2 and variable on timescales of days. A comparison with identical observations in 1995 implies that the object has brightened by at least 1.8 mag in R following the X-ray outburst. We also detected QX Nor in the IR in both quiescence and outburst. A faint source is visible in the J but not the R band in 1995 May. These first observations in the quiescent state yield magnitudes and colors consistent with optical emission from a low-mass companion in the binary system, as is true in other soft X-ray transients.

Subject headings: stars: individual (QX Normae) — X-rays: bursts — X-rays: stars

1. INTRODUCTION

X1608 – 52 is a soft X-ray transient (SXT) that exhibits large X-ray outbursts lasting tens of days on irregular timescales (~100 days to years; Lochner & Roussel-Dupre 1994). X1608 – 52 is an unusual source since the detection of type I X-ray bursts places it into the rare group of SXTs with neutron star primaries; most SXTs are black hole candidates. The only other member of this group with optical counterparts are Cen X-4 and Aql X-1. (For a review on candidates. The only other members of this group with optical counterparts are Cen X-4 and Aql X-1. (For a review on candidates. The only other members of this group with optical counterparts are Cen X-4 and Aql X-1. (For a review on candidates. The only other members of this group with optical counterparts are Cen X-4 and Aql X-1. (For a review on candidates. The only other members of this group with optical counterparts are Cen X-4 and Aql X-1. (For a review on candidates. The only other members of this group with optical counterparts are Cen X-4 and Aql X-1. (For a review on candidates. The only other members of this group with optical counterparts are Cen X-4 and Aql X-1.

2. OBSERVATIONS

2.1. Optical Photometry

CCD R- and I-band photometry of QX Nor was performed with the CTIO 0.9 m telescope on 1995 May 28 UT and on several occasions in 1996 May, June, and July.

Overscan and bias corrections were made for each CCD image with the task “quadproc” at CTIO to deal with the four-amplifier readout. The data were flat-fielded in the standard manner with IRAF.

Since there is only a single previously published finding chart of QX Nor (Grindlay & Liller 1978), obtained with photographic plates and of modest quality, a CCD image of the field from both 1995 and 1996 is displayed in Figure 1 (Plate 13). All comparison stars used in the analysis are marked. Due to the crowded field, all photometry was performed by point spread function fitting with DAOPHOT II (Stetson 1993). The instrumental magnitudes were transformed to the standard system through observations of several Landolt standard star fields (Landolt 1992). The magnitudes of QX Nor and several local comparison stars are listed in Table 1. The systematic error (from the transformation to the standard system) in these optical magnitudes is ±0.06 mag. The intrinsic 1 σ error of the relative photometry was derived from the rms scatter in the light curve of the comparison stars. The errors vary between ±0.01 and ±0.05 mag depending on the brightness of the stars (see Fig. 2).

2.2. Near-infrared Photometry

In addition to the optical photometry, near-infrared (IR) photometry of QX Nor was performed with the Cerro Tololo Infrared Imager (CIIRI) on the CTIO 1.5 m telescope on 1995 June 4 UT (J, Ks) and 1996 August 28 UT (J, K). CIIRI uses a 256 × 256 HgCdTe NICMOS3 array. All observations were taken in the f/13.5 mode resulting in a pixel scale of 0.65 pixel−1. Four 15 s exposures were co-added to obtain one frame. Each observation consisted of a mosaic of nine individual frames, with each frame shifted from the previous one by 20" to form a 3 x 3 grid centered on the position of QX Nor. Dark frames with identical integration times and flat field frames for each filter (derived from observations of an illuminated dome spot) were obtained on each night. First, a mean dark frame was subtracted from all observations. Next, a sky flat was constructed from a median of the scaled object frames and subtracted from each observation. Finally, the data were

1 Visiting Astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, operated by AURA, Inc., under cooperative agreement with the NSF.
divided by the normalized dome flat. To increase the signal-to-noise ratio and eliminate bad pixels, the shifted frames were aligned and combined with a bad pixel mask. A small section of the 1995 and 1996 J frames is displayed in the bottom panel of Figure 3 (Plate 13).

Again, photometry was performed by point spread function fitting with DAOPHOT II. The instrumental magnitudes were transformed to the CIT standard system through observations of Elias faint infrared standards (Elias et al. 1982). Only $K_s$ (a “short” $K$-band filter that reduces the sky background contributions) but no $K$ observations were taken in 1995. However, our IR observations of standard stars in 1996 show that the instrumental $K_s$ magnitudes are about 0.15 mag fainter than the $K$ magnitudes of the same objects, so that we can estimate the $K$ magnitude of QX Nor in 1995 from the $K_s$ observations. The results for QX Nor and several local comparison stars are listed in Table 1. The systematic errors in the IR photometry are $\pm 0.1$ mag, and the error in the relative photometry has been estimated to be between $\pm 0.1$ and 0.2 mag, again depending on the brightness of the stars.

### Table 1

| Object     | $R$  | $R-I$ | $J$  | $J-K$ |
|------------|------|-------|------|-------|
| QX Nor     | 20.2 | 1.45  | 17.2 | 1.5   |
| QX Nor     | > 22 | 0.98  | 14.2 | 0.6   |
| 1...........| 18.52| 0.99  | 16.3 | 0.8   |
| 2...........| 19.81| 1.65  | 15.8 | 1.0   |
| 3...........| 18.83| 1.10  | 16.1 | 0.8   |
| 4...........| 17.72| 1.12  | 15.0 | 0.7   |
| 5...........| 20.26| 1.56  | 16.8 | 0.8   |
| 6...........| 21.02| 2.31  | 15.1 | 1.7   |
| 7...........| 18.83| 1.02  | 16.3 | 0.7   |
| 8...........| 18.50| 1.02  | 16.2 | 0.7   |
| 9...........| 19.73| 1.70  | 15.7 | 1.1   |
| 10..........| 19.34| 2.00  | 14.2 | 1.7   |

* Nomenclature references in Fig. 1.
* $b$ Mean magnitude in outburst.
* $c$ In quiescence.

3. RESULTS AND DISCUSSION

Figure 1 shows two 600 s $R$-band exposures obtained in 1995 and 1996. Both frames reach a similar limiting magnitude, $R \approx 22$. Since QX Nor was at a mean magnitude of $R = 20.2$ during our 1996 postoutburst observations, it has brightened by at least 1.8 mag in $R$ from its quiescent state in 1995. We also obtained several $J$-band observations in 1996, but have no equivalent data from 1995 for comparison.

Figure 2 shows the relative $R$-band light curve of QX Nor and two local comparison stars. Both comparison light curves have been shifted by 1.5 mag for clarity of display. Comparison 6 is of the same brightness as the mean level of QX Nor. Therefore, the $1 \sigma$ error bars (0.05 mag) derived from the scatter in the comparison 6 light curve have been adopted for QX Nor. The data are insufficient to detect any periodicity, but it is obvious that the source is variable from night to night with a full amplitude of about 0.6 mag.

The bottom panel of Figure 3 displays a small section of the $J$ frames taken in 1995 and 1996. We detect QX Nor in both quiescence and outburst. A faint source is visible in $J$ but not $R$ in 1995 May. Due to its faintness ($J \approx 18$), we took care to confirm the IR detection of QX Nor in 1995 and exclude the possibility of a detector defect. The displayed image is a combination of nine shifted frames. The faint object is seen in each one of those separate frames and similarly in each one of nine separate $K_s$ frames (not displayed). The same is true for the 1996 $J$ and $K$-band data. The photometry indicates that QX Nor brightened by about 0.8 mag in $J$ and $K$ between 1995 May and 1996 August. Unfortunately, the seeing conditions during the 1996 observations were significantly worse than in 1995, which makes a direct comparison of the $J$ frames difficult.

Several type I X-ray bursts (as opposed to transient outbursts) have been observed from X1608 – 52. Assuming the Eddington luminosity during bursts that show spheric radius expansion (at least one such burst was seen by Nakamura et al. 1989) puts X1608 – 52 at a distance of 3.6 kpc. The extinction to the source can be estimated from the hydrogen column density ($N_H$) derived from X-ray spectral fits. Various $N_H$ values have been suggested for X1608 – 52 (Penninx et al. 1989; Mitsuda et al. 1989; Yoshida et al. 1993) ranging from $(1.0-2.0) \times 10^{22}$ cm$^{-2}$. Utilizing the relationship between $A_V$, $E(B-V)$, and the column density of Gorenstein (1975) leads to $4.5 \leq A_V \leq 9.1$. A more recent relationship between $A_V$ and $N_H$ based on ROSAT data by Predehl & Schmitt (1995) results in $5.6 \leq A_V \leq 11.2$. Together with a relationship between extinction and wavelength (Cardelli, Clayton, & Mathis 1989), and the additional constraint of the nondetection in $R$ ($R \gtrsim 22$), we arrive at the quiescent magnitudes and colors for QX Nor listed in Table 2.

For a SXT in quiescence, the main light source is most likely the secondary star. There is evidence for a disk in SXTs even in quiescence, but in most cases it contributes only 10%–30% of the light in the system in the optical regime (e.g., McClintock & Remillard 1990; Marsh, Robinson, & Wood 1994). Additionally, all of our observations are taken in the red and IR, and may therefore minimize any contribution from a hot accretion disk. Since we have no means of estimating the brightness of any accretion disk in X1608 – 52, we will assume that all light originates from the secondary for the following discussion. With the excep-
tion of GRO J0422+32 (M2 V, Filippenko, Matheson, & Ho 1995) and GRO J1655-40 (F5 IV, Bailyn et al. 1995), SXTs have been found to have K dwarf or subgiant companions; for example, Cen X-4 (K5–K7 V/V, McClintock & Remillard 1990; Shabaz, Naylor, & Charles 1993), Aql X-1 (G7–K3, Thorstensen, Charles, & Bowyer 1978; K5 V, Shabaz et al. 1996), A0620-00 (K5 V, McClintock & Remillard 1986; K3–K4 V, Haswell et al. 1993), X2023+338 (K0 IV, Casares & Charles 1994). For QX Nor, the faint magnitudes in quiescence exclude the possibility of a giant (luminosity class III) companion. If the secondary is a main-sequence star, a spectral type of about G0 provides a good match with our observed magnitudes and colors for a main-sequence star, a spectral type of about G0.

TABLE 2
QUIESCENT MAGNITUDES AND COLORS OF QX NORMAE

| Parameter | Gorenstein (1975) | Predehl & Schmitt (1995) |
|-----------|------------------|---------------------------|
| $A_V$      | $4.5 \leq A_V \leq 9.1$ | $5.6 \leq A_V \leq 11.2$ |
| $R_K$      | $R_0 \geq 18.6^a$, $R_0 \geq 15.2^a$ | $R_0 \geq 17.8^a$, $R_0 \geq 13.6^a$ |
| $J_H$      | $16.7 \geq J_H \geq 15.4$ | $16.4 \geq J_H \geq 14.8$ |
| $K_K$      | $16.0 \geq K_K \geq 15.5$ | $15.9 \geq K_K \geq 15.2$ |
| $(J-K)_0$  | $0.7 \geq (J-K)_0 \geq -0.1$ | $0.5 \geq (J-K)_0 \geq -0.4$ |

* For the low $A_V$-value.

† For the high $A_V$-value.

We can compare the two outbursts of X1608-52 for which optical and X-ray observations are available. Grindlay & Liller (1978) observed QX Nor at $I = 18.2 \pm 0.2$ about one month after the start of the 1977 outburst. Our I-band photometry shows QX Nor at a mean magnitude of $I = 18.5$ in data taken 5–6 months after the onset of the 1996 outburst. Figure 2 in Lochner & Roussel-Dupre (1994) displays an X-ray light curve of the 1977 outburst taken with the Vela 5B satellite, which can be compared to the X-ray light curve of the 1996 outburst (obtained from the quick look results made publicly available by the ASM/RXTE Team) in our Figure 4.

Our optical observations were taken when the X-ray flux of X1608-52 had returned to an average quiescent level of $\sim 2.6$ ASM counts s$^{-1}$ ($\sim 0.03$ Crab). The Grindlay & Liller (1978) observation was obtained during the outburst when the X-ray flux was still elevated. According to the X-ray light curve in Lochner & Roussel-Dupre (1994), the corresponding X-ray flux is $\sim 30$ Vela counts s$^{-1}$ ($\sim 0.75$ Crab). We observe essentially identical $I$ magnitudes at very different X-ray fluxes, indicating that the X-ray flux is not directly related to the optical brightness of the system. This is true for most SXTs: the optical counterparts of SXTs generally mimic the behavior observed in X-rays (a steep rise in brightness followed by a gradual decline); however, the optical flux falls much more slowly than the X-ray flux, so that the optical brightness is still enhanced when the X-ray flux has already returned to a quiescent level.

If we assume a gradual optical flux decay and a similar maximum optical brightness in both the 1977 and 1996 outbursts, it is surprising that QX Nor has not faded to fainter magnitudes in our 1996 observations, which were obtained much later after the onset of an outburst than those of Grindlay & Liller (1978). In order to compare the strength of the two outbursts, we tried to estimate the maximum X-ray flux during both outbursts, which might be indicative of the maximum optical brightness. We attempted to fit the 1996 X-ray outburst with an exponential or Gaussian profile analogous to the treatment in Lochner & Roussel-Dupre (1994). Unfortunately, there are no data from the ASM at the time of maximum, and we could not achieve a satisfactory fit. An exponential profile to the declining branch of the ASM X-ray light curve requires unreasonably high maximum count rates. Note that Kaluzienski & Holt (1977) report that the 1977 outburst was characterized by a very rapid rise followed by a "relatively stable plateau level" that lasted for about a month and finally a decline phase. It is also evident in Figure 2e of Lochner & Roussel-Dupre (1994) that an exponential fit does not represent the data particularly well. An outburst profile with a plateau level might also provide a better fit to the 1996 outburst. Since we cannot compare the two X-ray outbursts, the question of the relation between the two I magnitudes must remain unresolved.

Contrary to expectations, we also do not observe any declining trend in our 1996 R-band data. Figure 4 shows our optical observations with respect to the X-ray outburst. Although QX Nor displays some variability, no obvious overall fading is evident during a time span of two months. Yet, we know such fading must eventually occur, as these magnitudes are still significantly brighter than quiescence. A large number of black hole SXTs show secondary and tertiary maxima. One of the best examples is the light curve of V616 Mon (A0620-00), which displays the secondary maximum and a plateau-like state $\sim 200$ days after the outburst lasting for about 2 months, followed by a steep drop in brightness (Whelan et al. 1977). It is conceivable that our observations of QX Nor were made during such a state. If QX Nor brightens equally in every band, then our IR observations from 1996 August 28 could be an indication that the system has faded significantly, since it was only 0.8
mag brighter than in quiescence in $J$ (as opposed to the earlier 1.8 mag difference in $R$).

Chen, Livio, & Gehrels (1993) suggest a complete model for (black hole) SXTs based on the detailed structure in the X-ray and optical decay light curves, which predicts a specific correlation between X-ray and optical emission. It would be interesting to investigate whether there are differences in the decay light curves and the X-ray/optical correlation of systems with neutron star versus black hole primaries. X1608 – 52 is ideally suited for simultaneous optical/IR and X-ray observations during a future outburst due to its relatively short outburst recurrence time. Only two outbursts have been observed from Cen X-4 since 1969, while the outburst behavior of Aql X-1 is peculiar. In addition, QX Nor could be monitored for optical/IR variations in order to obtain its orbital period. Both Cen X-4 and Aql X-1 have relatively long orbital periods, 15.1 hr and 19.0 hr, respectively. X1608 – 52 is classified as an Atoll source and it has been suggested that Atoll sources as a group are characterized by short periods; all other known Atoll source periods are less than 5 hr. The determination of the orbital period of X1608 – 52 will show whether X1608 – 52 adheres to this general picture and/or whether long orbital periods are intimately related to the transient behavior in neutron star SXTs.

We thank Joanne Hughes, Eric Deutsch and Andrew Layden for obtaining some of the observations, and Don Hoard and Bruce Margon for reading a draft of this paper and providing helpful comments. This research was in part supported by NASA grant NAG 5-1630, and has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Bailyn, C. D., Orosz, J. A., McClintock, J. E., & Remillard, R. A. 1995, Nature, 378, 157
Berger, M., et al. 1996, ApJ, 469, L13
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Casares, J., & Charles, P. A. 1994, MNRAS, 271, L5
Chen, W., Livio, M., & Gehrels, N. 1993, ApJ, 408, L5
Elias, J. H., Frogl, J. A., Matthews, K., & Neugebauer, G. 1982, AJ, 87, 1029
Filippenko, A. V., Matheson, T., Ho, L. C. 1995, ApJ, 455, 614
Fujimoto, M. Y., & Gottwald, M. 1989, MNRAS, 236, 545
Gorenstein, P. 1975, ApJ, 198, 95
Grindlay, J. E., & Liller, W. 1978, ApJ, 220, L127
Hameury, J. M., King, A. R., & Lasota, J. P. 1986, A&A, 162, 71
Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79
Haswell, C. A., Robinson, E. L., Horne, K., Stiening, R. F., & Abbott, T. M. 1993, ApJ, 411, 802
Kaluzienski, L. J., & Holt, S. S. 1977, IAU Circ. 3099
Landolt, A. U. 1992, AJ, 104, 340
Lin, D. N. C., & Taam, R. E. 1984, in AIP Conf. Proc. 115, ed. S. E. Woosley (New York: AIP), 83
Lochner, J. C., & Roussel-Dupre, D. 1994, ApJ, 435, 840
Marsh, T. R., Robinson, E. L., & Wood, J. H. 1994, MNRAS, 266, 137
Marshall, F. E., Angelini, L., & XTE SOC Team. 1996, IAU Circ. 6331
McClintock, J. E., & Remillard, R. 1986, ApJ, 308, 110
———. 1990, ApJ, 350, 386
Mineshige, S., & Wheeler, J. C. 1989, ApJ, 343, 241
Mitsuda, K., Inoue, H., Nakamura, N., & Tanaka, Y. 1989, PASJ, 41, 97
Nakamura, N., Dotani, T., Inoue, H., Mitsuda, K., Tanaka, Y., & Matsuo, M. 1989, PASJ, 41, 617
Penninx, W., Damen, E., Tan, J., Lewin, W. H. G., & van Paradijs, J. 1989, A&A, 208, 146
Predehl, P., & Schmitt, J. H. M. M. 1995, A&A, 293, 889
Shabaz, T., Naylor, T., & Charles, P. A. 1993, MNRAS, 265, 655
Shabaz, T., Smale, A. P., Naylor, T., Charles, P. A., van Paradijs, J., Hassall, B. J. M., & Callanan, P. 1996, MNRAS, 282, 1437
Stetson, P. B. 1993, DAOPHOT II User’s Manual
Tanaka, Y., & Lewin, W. H. G. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 126
Thorstensen, J., Charles, P., & Bowyer, S. 1978, ApJ, 220, L131
van Paradijs, J., & McClintock, J. E. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 97
Whelan, J. A. J., et al. 1977, MNRAS, 180, 657
Yoshida, K., Mitsuda, K., Ebisawa, K., Ueda, Y., Fujimoto, R., & Yaqoob, T. 1993, PASJ, 45, 605
Fig. 1.—Left: 1995 600 s $R$-band exposure of the field of X1608—52 taken with the CTIO 0.9 m telescope. The field size is $90' \times 90'$. All comparison stars are marked. Right: 1996 600 s $R$-band exposure (MJD 50,276.1) of the same field. The arrow marks QX Nor.

WACHTER (see 485, 840)

Fig. 3.—Top: Small section of 1995 and 1996 $R$-band images to compare to bottom: 1995 and 1996 $J$-band images of the field of QX Nor. Each $J$ image is the average of nine 15 s images. QX Nor (arrow) is detected in $J$ as a faint source in both quiescence and outburst. North is up, and east is to the left.

WACHTER (see 485, 840)