OPTICAL EMISSION OF THE BLACK HOLE X-RAY TRANSIENT MAXI J1659−152 DURING QUIESCENCE

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ABSTRACT
We report on the optical detection of the black hole X-ray transient MAXI J1659−152 during its quiescent state. By using the Canada–France–Hawaii Telescope, we observed MAXI J1659−152 about seven months after the end of an X-ray outburst. The optical counterpart of MAXI J1659−152 is clearly detected with an $r'$-band magnitude of 23.6–23.8. The detection confirms that the optical emission of MAXI J1659−152 during quiescence is relatively bright compared to other black hole X-ray transients. This implies that the distance to MAXI J1659−152 is 4.6–7.5 kpc for an M2 dwarf companion star or 2.3–3.8 kpc for an M5 dwarf companion star. By comparing with other measurements, an M2 dwarf companion is more likely.

Key words: binaries: close – stars: individual (MAXI J1659−152) – X-rays: binaries

1. INTRODUCTION
Galactic black hole X-ray binary systems manifest themselves as X-ray novae and most of them are discovered via their sudden dramatic increase in X-ray brightness. Such an X-ray outburst is due to a change of the amount of material accreted from the companion star by the central compact object. In addition to X-ray follow-up observations following the evolution of the outburst, multi-wavelength observations play an important role in understanding the physics of these systems. In particular, reprocessing in the accretion disk and the companion star will also generate optical emission. We therefore expect to see a dramatic change in optical brightness when an X-ray nova is in outburst.

Optical observations provide the data necessary to determine the orbital period, the evolutionary state of the secondary, the binary mass function, and mass of the compact object itself. In combination with X-ray spectral and timing studies, these provide a detailed picture of the accretion process and the nature of the compact object. Although the optical counterpart of an X-ray nova is usually discovered during an outburst, observations when the source returns to quiescence are also extremely important. While the optical emission of an X-ray nova is very faint in quiescence, it is the best time to study the nature of the companion star and the geometry of the binary system, and to measure the mass function via radial velocity measurements.

The X-ray transient MAXI J1659−152 was first discovered with the Swift Burst Alert Telescope (BAT) on 2010 September 25 as a gamma-ray burst (GRB 100925A; Mangano et al. 2010). Independent discovery made with the Gas Slit Camera (GSC; Mihara et al. 2011) on board the Monitor of All-sky X-ray Image (MAXI; Matsuoka et al. 2009) suggested that it is a previously unknown Galactic X-ray transient. The optical counterpart of MAXI J1659−152 was discovered with the Swift UltraViolet/Optical Telescope (UVOT) immediately after the BAT trigger (Marshall 2010). Subsequent multi-wavelength observations from radio to hard X-ray showed that MAXI J1659−152 is a black hole binary candidate. In particular, frequent X-ray dips with a recurrent time of 2.4 hr were found in RXTE, Swift, and XMM-Newton observations (Kennea et al. 2011; Kuulkers et al. 2012). This strongly suggests that MAXI J1659−152 is a highly inclined system with an orbital period of 2.4 hr, the shortest among all the black hole X-ray binaries.

MAXI J1659−152 returned to quiescence as observed with Chandra on 2011 May 3 (Jonker et al. 2012), but it underwent a mini-outburst from 2011 May 6 (Yang & Wijnands 2011a, 2011b; Jonker et al. 2012). The source has finally settled down in the quiescent state from 2011 mid-August based on a Chandra monitoring program (Jonker et al. 2012).

The optical counterpart of MAXI J1659−152 has been monitored regularly with Swift UVOT and ground-based telescopes during the outburst (Russell et al. 2010; Yang et al. 2011; Yang & Wijnands 2011a, 2011b). In general, the optical activity tracked the X-ray outburst (Russell et al. 2010, 2011; Kong et al. 2011). The optical counterpart of MAXI J1659−152 is not detected in the Digitized Sky Survey indicating that the quiescent magnitude is >21. A tentative quiescent counterpart was reported by Kong et al. (2010) using the Pan-STARRS 1 (PS1) data. The source was only marginally seen in the image with an $r'$-band magnitude of ∼22.4. This was challenged by Kennea et al. (2011) and Kuulkers et al. (2012) noting that it is too bright for MAXI J1659−152.

In this Letter, we report our new deep optical imaging observation of MAXI J1659−152 in quiescence using the Canada–France–Hawaii Telescope (CFHT) aimed at measuring an accurate quiescent optical magnitude. We also re-analyzed the PS1 data for comparison.

2. OBSERVATIONS AND DATA ANALYSIS
2.1. CFHT
MAXI J1659−152 was observed with the MegaPrime/MegaCam at the CFHT on 2012 March 23. We checked the MAXI GSC daily data and the source was not detected in soft X-ray, indicating that it was likely in quiescence. However, we caution that if there is an X-ray mini-outburst, MAXI J1659−152 will not be detected with MAXI due to its low sensitivity. The MegaCam has an array of 36 CCDs, giving a total of $1^\circ \times 1^\circ$ field of view. We obtained two $r'$-band images under a seeing condition of ∼0.8 with an exposure time of 980 s each. The two images were separated by about 30 minutes.
The raw images were processed with Elixir\(^2\) for bias, flat field, overscan, bad pixel mask, and zero point.

We next corrected the CFHT images for the astrometry. By using 10 stars surrounding MAXI J1659−152, we used the IRAF task `ccmap` to compare with the USNO point source catalog. The resulting registration errors are 0.21'' in R.A. and 0.226'' in declination.

By examining the CFHT image together with images taken during the outburst (Russell et al. 2010; Kong et al. 2011; see also Figure 1), the optical counterpart of MAXI J1659−152 is clearly a variable (see Figure 1). We further compared the CFHT position of MAXI J1659−152 with the European very long baseline interferometry Network position (Paragi et al. 2010); the offset between the two positions is 0.043'', indicating that it is the true optical counterpart. We then performed aperture photometry using the task `phot` in IRAF. In addition to our target, we also measured the optical magnitude for a few nearby stars for checking (see Figure 1).

### 2.2. PS1

We also re-analyzed the PS1 image taken before the outburst of MAXI J1659−152 (Kong et al. 2010) by using the same method for the CFHT data. We obtained postage stamp images from the Postage Stamp Server maintained by the PS1 Image Processing Pipeline team at the University of Hawaii. As part of the 3\(\pi\) survey, the field of MAXI J1659−152 was observed with various filters several times each, but the source was only marginally seen with the \(r'\)-band filter taken on 2010 June 19.

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\(^2\) [http://www.cfht.hawaii.edu/Instruments/Elixir](http://www.cfht.hawaii.edu/Instruments/Elixir)
with an exposure time of 40 s. Since it is a few months before the first discovery of the outburst, the source should be in quiescence. As a check, the MAXI GSC light curve did not show any enhancement in the X-ray flux. Since MAXI J1659−152 is not in the $3\sigma$ survey catalog, we determined its magnitude by comparing with several cataloged stars. Like the CFHT data, we performed an aperture photometry for MAXI J1659−152 as well as the comparison and check stars. The magnitudes of the check stars measured by us are entirely consistent with the $3\sigma$ survey catalog.

### 3. RESULTS

In Table 1, we list the $r'$-band magnitudes of MAXI J1659−152 and a couple of check stars of the CFHT and PS1 observations. Given that our new CFHT observations were taken more than seven months after the end of an X-ray outburst confirmed by Chandra (Jonker et al. 2012) and there is no unusual X-ray activity shown in the MAXI GSC data, MAXI J1659−152 is likely in the quiescent state although we cannot totally rule out a mini-outburst or a very long optical decay. The $r'$-band magnitude of MAXI J1659−152 varied between 23.62 ± 0.06 and 23.81 ± 0.06 in 30 minutes. The two check stars near MAXI J1659−152 did not show any variability, indicating that MAXI J1659−152 is likely a variable star.

For the PS1 data, MAXI J1659−152 is marginally visible with a $r'$-band magnitude of 22.8 ± 0.3 (see Figure 1). This is roughly consistent with the quick-look analysis reported by Kong et al. (2010). We examined all the PS1 images in this field and the observation reported here has the best seeing and image quality among all the images. This may explain why MAXI J1659−152 was only detected in this observation. Furthermore, the CFHT images indicate that MAXI J1659−152 can be fainter than the PS1 measurement. It could happen that the PS1 observation was taken during a relatively bright state in the quiescence.

### 4. DISCUSSION

From both the CFHT and PS1 observations, we can conclude that the optical counterpart of MAXI J1659−152 shows variability during or near quiescence. In Figure 1, we also show an $R$-band image taken near the end of an outburst with the 1 m telescope at the Lulin Observatory in Taiwan (Kong et al. 2011). MAXI J1659−152 is clearly much fainter during our CFHT observations. Optical variability is quite common for black hole X-ray transients in quiescence. For example, GRS 1124−684, A0620-00, J0422+32, GS 2000+25, and V404 Cyg show flarings on timescales of a few minutes to 60 minutes with a typical amplitude of 0.1−0.6 mag (Zurita et al. 2003; Shahbaz et al. 2003, 2010). BW Cir (= GS 1354−64) is another quiescent black hole that exhibits large (0.5−1 mag) optical variability (Casares et al. 2009). The origin of optical flaring during quiescence is not well understood. Possible mechanisms include X-ray irradiation of the accretion disk (Hynes et al. 2004), magnetic reconnection events (Zurita et al. 2003), and direct synchrotron emission from an advective-dominated flow (Shahbaz et al. 2003). Simultaneous X-ray and optical observations are required to understand their nature (e.g., Hynes et al. 2004).

In addition to optical flaring activity, the orbital variation can contribute to the observed variability. MAXI J1659−152 is shown to have a 2.4 hr orbital period based on the dip-like events in the X-ray light curves (Kuulkers et al. 2012). In particular, the two CFHT observations are separated by about 30 minutes, equivalent to about 0.2 orbital phase. Variability is therefore not unexpected. The 0.2 mag difference is also consistent with other black hole X-ray transients with measured optical orbital modulation (e.g., see Figure 1 of Zurita et al. 2003). Future optical monitoring observations will be crucial to reveal the optical orbital modulation.

Our new CFHT observations strongly suggest that the proposed optical counterpart of MAXI J1659−152 is real and it shows noticeable variability that could be from flaring or orbital modulation. Even though we adopt the faintest measurement from our CFHT observations ($r'=23.8$), it is in contrast to the suggestion that the quiescent magnitude is $\gtrsim 27$ (Kuulkers et al. 2012). We note that the orbital modulation cannot produce such a huge optical variability ($\gtrsim 3$ mag) unless the compact object has strong radiation to evaporate the companion like black-widow-type pulsars (e.g., Kong et al. 2012). The suggested quiescent optical magnitude is based on a relationship between the optical outburst amplitude of an X-ray transient and the orbital period found by Shahbaz & Kuulkers (1998; hereafter SK98). With an orbital period of 2.4 hr, the $V$-band magnitude difference between the outburst and quiescence should be as large as 11 mag, yielding $V > 27$ in the quiescence. Taking the inclination effect into account, the quiescent $V$ magnitude is $\gtrsim 26.2$ (Kuulkers et al. 2012). By using previous PS1 measurement in the $r'$ band (Kong et al. 2010) and the limiting magnitudes of the PS1 $3\sigma$ survey, Kuulkers et al. (2012) derived an expected $V$-band magnitude of $V \gtrsim 22.8$; although it cannot rule out a much fainter object, a difference of at least 3 mag indicates that MAXI J1659−152 unlikely follows the SK98 relation. However, we caution that the SK98 relation is an empirical relation based on a sample of 11 black hole transients and there are many factors (e.g., the stellar type of the companion star, the inclination effect on the disk emission, and the peak mass transfer rate) affecting the correlation. Hence, scatter on the correlation is not unexpected.

To estimate the $V$-band magnitude, we first assume the spectrum of the companion. Given that MAXI J1659−152 is likely an M2 or M5 dwarf (Kuulkers et al. 2012; Jonker et al. 2012), the colors will become $B − V = 1.52$ (M2 dwarf) or $B − V = 1.61$ (M5 dwarf). We then correct the colors for the reddening assuming the Galactic values provided by Schlafly & Finkbeiner (2011). Using the transformation of Tonry et al. (2012), we get a reddened $r' − R$ color of 0.3 for both cases. The reddened $V−R = 1.9$ and 2.2 for an M2 dwarf and an M5 dwarf, respectively. This implies that $V−r' = 1.6$ (1.9) for an M2 dwarf (M5 dwarf). Using the observed $r'$-band magnitude (23.8) from our CFHT observation, we have $V = 25.4$ for an M2 dwarf and $V = 25.7$ for an M5 dwarf. These are consistent with the above limits derived by Kuulkers et al. (2012). In any case, the estimated quiescent $V$-band magnitude is within 1 mag difference for a high-inclination (80°) system although the difference could be as large as 2 mag for a lower inclination (65°) system.

### Table 1

| Source       | CFHT Epoch 1 | CFHT Epoch 2 | PS1 |
|--------------|--------------|--------------|-----|
| MAXI J1659−152 | 23.81 ± 0.06 | 23.62 ± 0.06 | 22.8 ± 0.3 |
| Check star 1  | 20.73 ± 0.004 | 20.731 ± 0.005 | 20.65 ± 0.05 |
| Check star 2  | 21.85 ± 0.01 | 21.86 ± 0.01 | 21.7 ± 0.1 |
Based on our new CFHT measurement, although the estimated V-band magnitude is still brighter, it is not a large offset as proposed by Kuulkers et al. (2012). As we mentioned above, there are other factors causing scatter on the SK98 correlation. For instance, the black hole X-ray binary XTE J1118+480 has an orbital period of 4.08 hr and the outburst amplitude is about 6–7 mag. According to SK98, the amplitude is at least 9.4 mag. However, XTE J1118+480 is underluminous in outbursts; the outburst X-ray spectra are hard in contrast to typical high/soft state of X-ray transients in outbursts, and the X-ray-to-optical flux ratio is low (∼5; see Zurita et al. 2006 for a discussion). Unlike XTE J1118+480, the X-ray spectral behaviors and X-ray-to-optical flux ratio of MAXI J1659–152 are similar to a typical X-ray transient in outburst (Kennea et al. 2011). Follow-up photometric and spectroscopic observations of MAXI J1659–152 in the future will be able to provide better constraints. On the other hand, the quiescent X-ray luminosity of MAXI J1659–152 as measured with Chandra is an order of magnitude higher than that derived from the orbital period–X-ray luminosity correlation (Jonker et al. 2012). Given that both optical and X-ray brightnesses are higher than expected, one simple explanation is that MAXI J1659–152 is not in a true quiescent state. It is worth noting that some short orbital period black hole systems have a long decay time. For example, GRO J0422+32 reached its optical quiescent state 760 days after an outburst (Garcia et al. 1996). Further optical and X-ray observations will confirm this.

We can now use the absolute magnitude of the companion to estimate the distance to the source. The absolute V-band magnitude of an M2 dwarf and an M5 dwarf is 10 and 11.8, respectively. Since $V - R = 1.5 (1.8)$ for an M2 (M5) dwarf, this implies that $M_R$ is 8.5 (10). By using the transformation of Tonry et al. (2012), $M$ becomes 8.77 (10.27). Comparing with the reddening ($A_v = 1.4$; Schlafly & Finkbeiner 2011) corrected $r'$-band magnitude, the distance is 5.3 kpc (M2 dwarf) or 2.7 kpc (M5 dwarf). If we further assume the accretion disk contributes 50% of the visible light (see Jonker et al. 2012), then the distance would be between 7.5 kpc (M2 dwarf) and 3.8 kpc (M5 dwarf). If $A_v$ is as large as 1.7 (Schlegel et al. 1998), then the distance to MAXI J1659–152 will be 4.6–6.5 kpc and 2.3–3.3 kpc for an M2 dwarf and an M5 dwarf, respectively. Comparing with previous estimations (e.g., Kennea et al. 2011; Kaur et al. 2012; Kuulkers et al. 2012; Jonker et al. 2012), an M2 dwarf companion star is more likely. This is also consistent with the conclusion made by Jonker et al. (2012).

On the other hand, if MAXI J1659–152 has an M5 dwarf companion star and a distance of ~2 kpc, the observed X-ray luminosity will be consistent with the orbital period–X-ray luminosity correlation (Jonker et al. 2012). Future optical spectroscopy during quiescence will be crucial to determine the stellar type of the companion star and hence the distance to the system. In addition, an ellipsoidal light curve modeling during quiescence will allow us to derive the inclination angle of the system. These observations will also test if the SK98 correlation holds for MAXI J1659–152. Combining with a deep X-ray observation during the quiescent state, we could constrain the orbital period–X-ray luminosity correlation.

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Facilities: CFHT, PS1

REFERENCES

Casares, J., Orosz, J. A., Zurita, C., et al. 2009, ApJS, 181, 238
Garcia, M. R., Callanan, P. J., McClintock, J. E., & Zhao, P. 1996, ApJ, 460, 932
Hynes, R. I., Charles, P. A., Garcia, M. R., et al. 2004, ApJ, 611, L125
Jonker, P. G., Miller-Jones, J. C. A., Homan, J., et al. 2012, MNRAS, 423, 3308
Kaur, R., Kaper, L., Ellerbroek, L. E., et al. 2012, ApJ, 746, L23
Kennea, J. A., Romano, P., Mangano, V., et al. 2011, ApJ, 736, 22
Kong, A. K. H., Huang, R. H. H., Cheng, K. S., et al. 2012, ApJ, 747, L3
Kong, A. K. H., Li, C.-C., Chen, Y.-T., et al. 2010, Atel, 2976
Kong, A. K. H., Yang, Y. J., & Wijnands, R. 2011, Atel, 3524
Kuulkers, E., Kouveliotou, C., Belloni, T., et al. 2012, A&A, submitted (arXiv:1204.5840)
Mangano, V., Hoversten, E. A., Markwardt, C. B., et al. 2010, GCN Circ., 11296
Marshall, F. E. 2010, GCN Circ., 11298
Matsuoka, M., Kawasaki, K., Ueno, S., et al. 2009, PASJ, 61, 999
Mihara, T., Nakajima, M., Sugizaki, M., et al. 2011, PASJ, 63, S623
Paragi, Z., van der Horst, A. J., Granot, J., et al. 2010, Atel, 2906
Russell, D. M., Lewis, F., Bersier, D., et al. 2010, Atel, 2884
Russell, D. M., Lewis, F., Schreuder, L., et al. 2011, Atel, 3517
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Shahbaz, T., Dhillon, V. S., Marsh, T. R., et al. 2003, MNRAS, 346, 1116
Shahbaz, T., Dhillon, V. S., Marsh, T. R., et al. 2010, MNRAS, 403, 2167
Shahbaz, T., & Kuulkers, E. 1998, MNRAS, 295, L1
Tonry, J. L., Stubbs, C. W., Lykke, K. R., et al. 2012, ApJ, 750, 99
Yang, Y. J., & Wijnands, R. 2011a, Atel, 3339
Yang, Y. J., & Wijnands, R. 2011b, Atel, 3379
Yang, Y. J., Wijnands, R., & Russell, D. M. 2011, Atel, 3249
Zurita, C., Casares, J., & Shahbaz, T. 2003, ApJ, 582, 369
Zurita, C., Torres, M. A. P., Steeghs, D., et al. 2006, ApJ, 644, 432