X-Ray Pulsar XTE J1858+034: Discovery of the Cyclotron Line and the Revised Optical Identification

Sergey S. Tsygankov1,2, Alexander A. Lutovinov2, Sergey V. Molkov2, Anlauf A. Djupvik3,4, Dmitry I. Karasev2, Victor Doroshenko2,5, Alexander A. Mushotkov6,7, Christian Malacaria8,9, Peter Kretschmar10, and Juri Poutanen1,2,11

1 Department of Physics and Astronomy, FI-20014 University of Turku, Finland; sergey.tsygankov@utu.fi
2 Space Research Institute of the Russian Academy of Sciences, Profsoyuznaya Str. 84/32, Moscow 117997, Russia
3 Nordic Optical Telescope, Apartado 474, E-38700 Santa Cruz de La Palma, Santa Cruz de Tenerife, Spain
4 Department of Physics and Astronomy, Aarhus University, NyMunkegade 120, DK-8000 Aarhus C, Denmark
5 Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D-72076 Tübingen, Germany
6 Leiden Observatory, Leiden University, NL-2300RA Leiden, The Netherlands
7 Pulkovo Observatory, Russian Academy of Sciences, Saint Petersburg 196140, Russia
8 NASA Marshall Space Flight Center, NSSTC, 320 Sparkman Drive, Huntsville, AL 35805, USA
9 European Space Agency (ESA), European Space Astronomy Centre (ESAC), Camino Bajo del Castillo s/n, E-28692 Villanueva de la Caada, Madrid, Spain
10 European Space Agency (ESA), European Space Astronomy Centre (ESAC), Camino Bajo del Castillo s/n, E-28692 Villanueva de la Caada, Madrid, Spain

Received 2020 November 4; revised 2021 January 12; accepted 2021 January 18; published 2021 March 15

Abstract

We present the results of a detailed investigation of the poorly studied X-ray pulsar (XRP) XTE J1858+034 based on the data obtained with the NuSTAR observatory during the outburst of the source in 2019. The spectral analysis resulted in the discovery of a cyclotron absorption feature in the source spectrum at ~48 keV in both the pulse phase-averaged and resolved spectra. Accurate X-ray localization of the source using the NuSTAR and Chandra observatories allowed us to accurately determine the position of the X-ray source and identify the optical companion of the pulsar. The analysis of the counterpart properties suggested that the system is likely a symbiotic binary hosting an XRP and a late-type companion star of the K-M classes rather than a Be X-ray binary as previously suggested.

Unified Astronomy Thesaurus concepts: Accretion (14); Stellar accretion disks (1579); Magnetic fields (994); Binary pulsars (153); Neutron stars (1108); High mass x-ray binary stars (733); X-ray binary stars (1811)

1. Introduction

The transient X-ray pulsar (XRP) XTE J1858+034 was discovered with the All Sky Monitor (ASM) on board the RXTE observatory in 1998 (Remillard et al. 1998). Pulsations with a period of 221.0 ± 0.5 s detected during the same outburst in the RXTE/PCA data (Takeshima et al. 1998) and the transient nature of XTE J1858+034 led these authors to conclude that the system is likely an XRP with a Be counterpart. A long-term light curve based on the RXTE/ASM data clearly shows regular outbursts with a period of ~380 days, which was interpreted as the orbital period of the binary system (Doroshenko et al. 2008).

The energy spectrum of XTE J1858+034 is typical for XRPs and can be described as an absorbed cutoff powerlaw with an equivalent hydrogen column density of 6 × 1022 cm−2, modified by an iron emission line around 6.6 keV (Paul & Rao 1998). A similar spectral shape and parameters were obtained from INTEGRAL data (Filippova et al. 2005; Doroshenko et al. 2008) collected during an outburst in 2004 (Molkov et al. 2004). Evidence of a cyclotron absorption line has never been reported for XTE J1858+034 in the literature; therefore, the magnetic field strength of the neutron star (NS) remains uncertain. On the other hand, Paul & Rao (1998) discovered quasiperiodic oscillations at 0.11 Hz, which is significantly higher than the spin frequency. Interpreting this feature in the frame of the beat frequency model, they estimated the NS magnetic field to be 0.8 × 1012 G, where r_kpc is the distance to the system in kiloparsecs.

The X-ray localization of XTE J1858+034 was originally obtained from the RXTE data (Marshall et al. 1998) and later improved by Molkov et al. (2004) using the observations with INTEGRAL/JEM-X and INTEGRAL/IBIS/ISGRI. Based on these results, Reig et al. (2005) proposed a star with the coordinates R.A. = 18h58m36s, decl. = 3°26′09″ as a possible counterpart for the source. Optical spectroscopy indicated that it was the only nearby star exhibiting Hα emission; however, its position was not consistent with the JEM-X uncertainty. Therefore, this association can only be considered tentative.

The relative faintness of XTE J1858+034 even during its outbursts and shortage of available data did not allow for making any definitive conclusions regarding the physical properties of the NS in the system to date. Here we report the results of a NuSTAR observation of XTE J1858+034 performed during its outburst in the fall of 2019 (detected by the MAXI instrument; Nakajima et al. 2019), which allowed for conducting a detailed spectral and timing analysis and localizing the source.

2. Observations and Data Reduction

This work is based on several data sets in the X-ray (Chandra, XMM-Newton, and NuSTAR observatories) and near-IR (the UKIDSS survey and NOT) bands. The complete list of the data used is presented in Table 1.

2.1. NuSTAR Observatory

The NuSTAR observatory includes two identical coaligned X-ray telescopes focusing X-ray photons onto two focal plane modules, A and B (FPMA and FPMB; Harrison et al. 2013). In
of the project aimed at studies of the transient XRP s in a quiescent state (Tsygankov et al. 2017b). For the data reduction, we used the software package CIAO v4.12 with an up-to-date CALDB v4.9.1. The procedure CELLDTECT was used to determine the coordinates of the sources in the Chandra field of view. The source spectrum was extracted from a circular aperture with a radius of 3″ around the position, while for the background extraction, we used a circular region near the source with a radius of 15″.

2.4. Nordic Optical Telescope

Optical and near-IR observations were obtained at the NOT through applications in the fast-track service (Djupvik & Andersen 2010) using the standby CCD camera StanCam and the NOT near-IR camera and spectrograph (NOTCam13). StanCam images in the BVRI bands, as well as NOTCam high spatial resolution images (0.079 pixel−1) in the JHKs bands, were obtained on 2016 April 20 in good seeing conditions (FWHM = 0.6–0.7). The near-IR images were obtained by small step dithering in a 3 × 3 pattern with 30 s exposures in each position obtained in ramp-sampling mode, reading out every 5 s, giving a total of 540 s filter−1 in the combined J, H, and Ks images. The StanCam exposures of 120 s showed no detection in any band, while the near-IR images detected a red counterpart at the location of the X-ray source. A K-band spectrum was obtained on 2016 September 15 under less favorable conditions. The setup used was the WF camera (0.234 pixel−1), grism 1 with a dispersion of 4.1 Å pixel−1; the 128 μm slit (0.6 wide); and the K-band filter (number 208) used as an order sorter, which gives a resolution of 10.5 Å and resolving power of λ/Δλ = 2100. The spectra were obtained in the ABBA dithering mode, exposing 600 s position−1 and using the ramp-sampling mode to read out nondestructively 10 times every 60 s. In situ arc and halogen lamps were observed to take out the effect of fringing as much as possible and account for flexure in the wavelength calibration. A telluric standard close to the target was observed immediately before the target.

The near-IR images were reduced using the NOTCam IRAF package to do bad-pixel correction, flat-fielding with differential twilight flats, sky subtraction, and shifting and median combining of the individual images. The individual 2D K-band spectra were hot- and zero-pixel-corrected, flat-fielded, and sky-subtracted before 1D extraction using standard IRAF tasks. The individual 1D spectra were wavelength-calibrated and thereafter combined into a final spectrum. This was divided by the telluric standard spectrum to correct for atmospheric features and afterward multiplied by a blackbody continuum of the same spectral type as the telluric standard to correct the slope in the spectrum. Due to mediocre sky conditions, the final spectrum had a poor S/N ratio and was therefore smoothed over 17 pixels, lowering the resolving power to R = 120.

3. Results

The XRP XTE J1858+034 was observed by the NuSTAR observatory close to the peak of the 2019 outburst. The light curve of the source in the 15–50 keV energy band obtained14 by the Burst Alert Telescope on board the Neil Gehrels Swift Observatory (Swift/BAT; Krimm et al. 2013) is shown in

13 http://www.not.iac.es/instruments/notcam/
14 http://swift.gsfc.nasa.gov/results/transients/
The relatively high brightness of the source allowed us to study its properties in a broad energy band in detail. At the same time, soft-band Chandra and XMM-Newton data were collected in the low state with low counting statistics that were insufficient to detect pulsations. All uncertainties in the paper are reported at a 1σ confidence level, unless otherwise stated.

3.1. Pulse Profile and Pulsed Fraction

Orbital parameters, except for the orbital period, are not known for XTE J1858+034. Considering that the available X-ray data only cover a small fraction of the orbit, it was also impossible to determine those based on the X-ray timing. Therefore, for the timing analysis, only the barycentric but no binary correction was applied to the light curves. Using a standard epoch folding technique (EFSEARCH task of FTOOLS; Leahy 1987), strong pulsations in the full band were found with the period \( P = 218.382(2) \) s. The uncertainty for the pulse period value was determined from the simulated light curves following the procedure described by Boldin et al. (2013).

High count statistics allowed us to reconstruct the pulse profile of the source in several energy bands (selected to provide a sufficient number of photons in each) from 3 to 79 keV (see Figure 2). Even at the highest energies (in the 40–80 keV band), where counting statistics are limited, pulsations at an expected period are significantly detected in a blind search (Lomb–Scargle false-alarm probability \( p \sim 2.8 \times 10^{-7} \) for over 2.5 million trial periods). The overall shape of the pulse profile is sine-like single-peaked, consistent with the results from the INTEGRAL observatory obtained by Doroshenko et al. (2008). We note, however, that although the pulse profile shape remains constant at different energies, some tentative sign of a phase lag is observed, with the soft profile lagging the hard one.

Based on the energy-resolved pulse profiles with 12 phase bins, we also calculated the pulsed fraction\(^{15}\) as a function of energy presented in Figure 3. The linear increase of the pulsed fraction toward higher energies can be clearly seen, which is consistent with the typical behavior of most XRPs (Zhitnikov & Tsygankov 2009).

3.2. Phase-averaged Spectral Analysis

Previously, the spectral properties of XTE J1858+034 in the X-ray band were studied using RXTE and INTEGRAL data (Paul & Rao 1998; Filippova et al. 2005; Doroshenko et al. 2008). In both cases, it was concluded that the source spectrum can be fit with an absorbed power law with a high-energy exponential cutoff, i.e., the typical spectrum for XRPs. No evidence for other features, such as cyclotron lines, was reported.

The NuSTAR observatory, owing to a sufficiently high-energy resolution and much better sensitivity at high energies, allowed us to conduct a much more detailed search for the possible cyclotron lines in the source spectrum. Similarly to RXTE and INTEGRAL, the NuSTAR spectrum below \( \sim 40 \) keV can be well described with several continuum

\(^{15}\text{Here PF} = (F_{\text{max}} - F_{\text{min}})/(F_{\text{max}} + F_{\text{min}})\text{, where } F_{\text{max}} \text{ and } F_{\text{min}} \text{ are the maximum and minimum fluxes in the pulse profile, respectively.}\)
models. In particular, we attempted to fit the data with several phenomenological continuum models commonly used for XRP, i.e., the Comptonization model (COMPTT in XSPEC) and a power law with a high-energy exponential cutoff (CUTOFFPL or PO × HIGHECUT in XSPEC). A more detailed study of different phenomenological and physical models applied to the source spectrum is presented in the accompanying paper by Malacaria et al. (2021).

To get an adequate fit, photoelectric absorption at low energies (PHABS in XSPEC, assuming the standard solar abundance from Anders & Grevesse 1989) and a fluorescent iron emission line (GAU in XSPEC) were introduced to the model. However, irrespective of the continuum model we used, residuals around ∼45 keV in absorption are also immediately apparent in the phase-averaged spectrum of XTE J1858+034. Figure 4 demonstrates the case of the COMPTT continuum model (see panel (c)), but similar residuals also appear with other models. The fit can be greatly improved by inclusion of a Gaussian absorption line in the model (Figure 4(b)). The best-fit spectral parameters are presented in Table 2. Inclusion of an absorption line with energy 47.7(2) keV improves the fit from χ²/dof = 2926.8/1685 to χ²/dof = 1909.3/1682. The high statistical significance of the feature is obvious from the huge Δχ² value. Its proper estimate using the XSPEC script SIMFTEST is technically infeasible due to an unrealistically large number of required simulations (the largest χ² change obtained in 10⁴ simulations was only 48), which allows us to conclude that the significance estimated using this method must be high and, in any case, more than 3σ. Applying the F-test, we calculated a false-detection probability for the line of P = 2.0 × 10⁻¹⁵⁵.

The detection of a cyclotron line at ∼48 keV implies a magnetic field in XTE J1858+034 of ∼5.2 × 10¹² G, assuming a gravitational redshift z = 0.26 for the typical NS parameters (R = 12 km and M = 1.5 M☉). Applying the CYCLABS model instead of GABS to describe the line results in a lower cyclotron energy of ∼44 keV. The discrepancy between these two models is related to their definition and was found in other studies (e.g., Nakajima et al. 2010; Mushtukov et al. 2015b; Doroshenko et al. 2017); see also the discussion of different line models in the review of Staubert et al. (2019). We emphasize only that it should be kept in mind when comparing results from different studies.

In the quiescent state, XTE J1858+034 was observed twice: in 2006 April with XMM-Newton and 2013 February with Chandra. In both cases, the source was found in the very low state with the flux about 3 orders of magnitude lower than in our NuSTAR observation. Both spectra were fitted with an absorbed power law (PHABS × POW in XSPEC) and blackbody (PHABS × BB in XSPEC) in order to determine the origin of the source emission in quiescence. A systematic study of the quiescent emission in transient XRP with Be optical companions was described by Tsygankov et al. (2017b); however, XTE J1858+034 was excluded from their sample due to the uncertain nature of its optical counterpart.

Taking into account the small number of collected photons, the spectra in the low state were binned to have at least one count in each energy channel and fitted using the W-statistics (Wachter et al. 1979). For the same reason, it was impossible to constrain the absorption column simultaneously with other parameters. Therefore, we fixed it at the best-fit value obtained from the NuSTAR data (N_H = 7.5 × 10²² cm⁻²). The best-fit spectral parameters in the soft X-ray band are presented in Table 3. It is clear that both models can fit the data equally well.

We also fitted XMM-Newton MOS and pn data jointly using the same simple models but with N_H as a free parameter in order to check if the absorption value depends on the luminosity state of the source. As a result, for the blackbody model, we obtained N_H = (1.8±0.7) × 10²² cm⁻² and temperature kT = 2.1±0.3 keV; for the power law, we obtained N_H = (3.8±2.0) × 10²² cm⁻² and photon index 0.9±0.7. With a similar quality of the fit, we cannot make any final conclusions on the possibility of lower absorption in the quiescent state.
Both Chandra and XMM-Newton observed XTE J1858+034 shortly after the flares and measured hard spectra (i.e., both have low photon indexes or high blackbody temperatures) and fluxes. The hard spectral shape points to a likely nonthermal origin of the emission (Tsygankov et al. 2017b). The source exhibits regular outburst activity, and persistent accretion between flares cannot be excluded. Moreover, owing to the long spin period, XTE J1858+034 may belong to the group of pulsars accreting from a cold low-ionized disk even in a quiescent state (Tsygankov et al. 2017a).

3.3. Phase-resolved Spectral Analysis

The high counting statistics of the NuSTAR data allowed us to perform a pulse phase-resolved spectral analysis. For that, we used our best-fit model from the phase-averaged spectroscopy (PHABS × (GAU + COMPTT) × GABS) and the phase binning shown in Figure 2, which was defined based on the available counting statistics and observed pulse profile morphology. The source spectral parameter variations over the pulse are shown in Figure 5. Based on the SIMFTEST simulations, the significance of the cyclotron line in all phase-resolved spectra was shown to be higher than 3σ.

We see that the continuum parameters (temperature and optical depth of the Comptonizing plasma) vary significantly, whereas the relatively large uncertainty on the cyclotron line parameters prevent us from making any conclusion on their stability. The fitted values for the absorption column, iron line parameters, and temperature of the seed photons stay constant within the errors over the pulse.

3.4. X-Ray Position

The original localization accuracy of XTE J1858+034 obtained with the RXTE observatory was 6′ (Remillard et al. 1998). This was further improved by Marshall et al. (1998) based on repeated scans across the source with the RXTE/PCA instrument, which allowed to localize the source at R.A.(2000) = 18^h58^m38^s, decl. (2000) = 3°21′, with a 90% confidence error radius of 2.5′. Later, using the imaging capabilities of the JEM-X and IBIS telescopes on board the INTEGRAL observatory, Molkov et al. (2004) further constrained the coordinates of XTE J1858+034 as R.A. = 18^h58^m36^s, decl. = 3°26′06″ for the IBIS/ISGRI data with the 2′ uncertainty and R.A. = 18^h58^m44^s, decl. = 3°26′02″ for the JEM-X data with the 1′ uncertainty. The X-ray image of the sky field obtained with the Chandra observatory is shown in Figure 6. Two weak X-ray sources compatible with these localization regions were found in the data.

In order to determine the nature of XTE J1858+034, Reig et al. (2005) performed optical photometric and spectroscopic observations of the field around the best-fit INTEGRAL position. It was revealed that only one star with the coordinates R.A. = 18^h58^m36^s, decl. = 3°26′09″ exhibits Hα emission (marked with a white plus sign in Figure 6). This star was proposed to be a possible counterpart of XTE J1858+034, since the counterpart was expected to be a Be star.

However, Figure 6 demonstrates that this star cannot be an optical companion of XTE J1858+034 (source marked with the number 1). This conclusion is confirmed by at least three facts: coincidence of the localization regions obtained by INTEGRAL/JEM-X and NuSTAR (see green contours in Figure 6), detection of X-ray pulsations with a period of ∼221 s by NuSTAR, and coincidence of the NuSTAR and Chandra positions.

Using our Chandra data, we obtained the precise coordinates for XTE J1858+034 of R.A. = 18^h58^m43.64′, decl. = 3°26′05.8″ (J2000, marked with the number 1 in Figure 6) using the WAVDETECT tool from the CIAO package. A statistical uncertainty

| Parameter | Chandra | XMM-Newton |
|-----------|---------|------------|
| $N_\text{H}$ (10^{22} cm$^{-2}$) | 7.5$^{+0.4}_{-0.6}$ | 1.7 ± 0.9 |
| $\Gamma$ | $-0.4 \pm 0.7$ | 105.5 (119) |
| C-value (dof) | 27.5 (23) | |
| Flux$^a$ (erg s$^{-1}$ cm$^{-2}$) | $4.2_{-0.3}^{+0.5} \times 10^{-13}$ | $4.3_{-0.5}^{+0.4} \times 10^{-13}$ |
| PHABS × BB Model |
| $N_\text{H}$ (10^{22} cm$^{-2}$) | 7.5$^{+0.4}_{-0.6}$ | |
| $kT_{\text{bb}}$ (keV) | $2.5_{-0.3}^{+0.5}$ | $1.4_{-0.4}^{+0.6}$ |
| C-value (dof) | 27.4 (23) | 104.9 (119) |
| Flux$^a$ (erg s$^{-1}$ cm$^{-2}$) | $3.5_{-0.5}^{+0.3} \times 10^{-13}$ | $2.8_{-0.5}^{+0.4} \times 10^{-13}$ |

Note. $^a$ Unabsorbed flux in the 0.5–10 keV energy band.
of 0.8 at the 90% confidence level was obtained following the recommendations available on the online threads.\textsuperscript{16} Taking into account the systematic uncertainty of the Chandra absolute positions of the same value,\textsuperscript{17} the resulting localization accuracy of the source we obtained is 1σ (90% confidence level radius; see blue circle in Figure 7).

4. Discussion

4.1. Structure of the Emitting Region

The observational properties of X-ray emission from XRPs depend on the physical conditions and geometrical structure of the emitting regions at the NS surface and thus can be used to probe them. As was already mentioned in Section 3.1, the pulse profile of XTE J1858+034 has a sine-like single-peaked shape that is almost independent of energy. At the same time, some tentative sign of a phase lag is observed, with the soft profile lagging the hard one. A quantitative interpretation of this phenomenon is not possible in the absence of adequate models describing the emission of XRPs; however, qualitatively, one may speculate that it may be associated with the resonant scattering of X-ray photons by the accretion flow above the hot spot. Indeed, considering that the source is likely in the subcritical regime of accretion (see below), the optical thickness of the accretion flow above the hot spot is below unity for a nonresonant scattering. Thus, the low-energy photons ($E < 25$ keV) leave the system freely with a pencil-beam emission diagram (Basko & Sunyaev 1975). However, the scattering cross section near the cyclotron energy ($E_{\text{cyc}} = 48$ keV; see below) is well above unity (Herold 1979; Daugherty & Harding 1986). Because of that, the cyclotron photons are scattered by the accretion flow. This results in an energy-dependent beam function, leading to the observed lag between the pulse profiles.

Variations of the spectral continuum over the pulse phase are also consistent with a pencil-beam emission diagram. From Figure 5, one can also notice that the optical depth $\tau$ appears to correlate with the flux in the profile, whereas the plasma temperature $kT$ shows an anticorrelation (except main minimum around zero phase) reaching maximum values in the wings of the flux peak (see Figure 5(e)). This behavior can be interpreted in terms of the subcritical accretion onto a strongly magnetized NS with a pencil-beam emission diagram. In this case, the accretion flow loses its kinetic energy in the atmosphere of an NS, resulting in the inverse temperature profile in the NS atmosphere with hotter upper layers where most of energy is released (Basko & Sunyaev 1975). The maximal flux in the pulse profile corresponds to the situation when an observer looks at a hot spot close to the local normal. Then, photons from the deeper and colder layers are detected, resulting in a negative/positive correlation of temperature/optical depth with the photon energy flux. This result points to a pencil-beam pattern for the pulsars operating in a subcritical regime. The estimated luminosity of XTE J1858+034 during our NuSTAR observation is $L \sim 2 \times 10^{37}$ erg s$^{-1}$ for a distance of 10 kpc (see below), whereas the critical luminosity for the pulsar with magnetic field $B \sim 5 \times 10^{12}$ G is expected to be around $3 \times 10^{37}$ erg s$^{-1}$ (Mushtukov et al. 2015a). Thus, one may conclude that XTE J1858+034 was observed very close to the critical luminosity but still in the subcritical regime.

4.2. Origin of the IR Companion

The study of optical catalogs and observational data showed the absence of any object in the localization region of the X-ray source. The upper limit on the observed magnitudes in filters $g$, $r$, and $i$, according to the Pan-STARRS instrumental filters, is around 23.1.

Inspecting the UKIDSS catalog,\textsuperscript{18} we found that the position of XTE J1858+034 determined from the Chandra data is compatible with a faint infrared star, which, in turn, is apparently blended with another one (Figure 7(a)). The blue circle illustrates an uncertainty of the source X-ray position. Based on the UKIDSS data, it is impossible to separate the fluxes from these stars to measure the correct magnitudes of the counterpart in the near-IR bands. Therefore, to measure the characteristics of the counterpart of XTE J1858+034, we performed observations with the NOT in several filters ($BVRiJHK_s$). The image of the sky field around XTE J1858+034 obtained with NOTCam in the $K_s$ filter is shown in

\textsuperscript{16} https://cxc.harvard.edu/ciao/threads/wavdetect/

\textsuperscript{17} https://cxc.harvard.edu/cal/ASPECT/cellon/

\textsuperscript{18} http://wsa.roe.ac.uk/
Thus, the only infrared log l o g 3, decl. indicated.

Improved the S conditions. Smoothing the spectrum over 17 pixels, however, and converting them into (Figure 9. Left: StanCam i-band image with exposure of 120 s. Right: NOTCam HJK, color-coded image, each 540 s. The green arrow shows the IR companion of XTE J1858+034. Both have N up and E left and show the same region.

Figure 9. The K-band spectrum of the IR counterpart of XTE J1858+034. The locations of the CO 2–0, 3–1, and 4–2 band heads at 2.29, 2.32, and 2.35 μm are indicated.

Figure 7(b). It is clearly seen that the two objects are perfectly separated by a distance of 0″7; thus, the only infrared companion of the source in the NOTCam data is a star with the coordinates of R.A. = 18h58m43s.63, decl. = 3°26′05″.2 (J2000).

The StanCam BVRi images obtained at the NOT in good seeing show no detection at the location; see the i-band image compared to the JHK color image in Figure 8. Photometric analysis of the NOT data using point-spread function photometry (DAOPHOT II) allowed us to determine the magnitudes of this star as J = 18.559 ± 0.037, H = 15.291 ± 0.035, and K = 13.520 ± 0.027. Note that, for calibrating instrumental magnitudes JHK, and converting them into JHK ones, we used the GPS/UKIDSS catalog as a reference.

The K-band spectrum obtained with NOTCam resulted in a very low S/N ratio of around 7 due to less than optimal conditions. Smoothing the spectrum over 17 pixels, however, and thereby lowering the resolving power from 2100 to 120, improved the S/N to 20 and revealed a tentative detection of the CO 2–0, 3–1, and 4–2 band heads in absorption at 2.29, 2.32, and 2.35 μm, respectively, of which the latter is cut halfway by the instrument sensitivity; see Figure 9. The rms in the smoothed spectrum is of the order of 5%, and the depth of the features is around 15%, giving a 3σ detection. As shown in the K-band spectral catalog of Wallace & Hinkle (1997), the presence of these CO bands in absorption strongly suggests a late spectral type of luminosity class I or III.

The equivalent width estimate for the 2–0 band head at 2.297 μm is 24 A, which would point to a late M-type giant or early M-type supergiant according to the relation between spectral type and CO equivalent widths in Figure 2 in Davies et al. (2007). The 3–1 band head at 2.323 μm is even broader but also more contaminated with noise. We believe it is fairly safe to deduce that the object is a late type, most likely an M-type giant or supergiant. The rest of the spectrum remains featureless, although there is a small bump below detection levels at the position of Brγ.

Some conclusions can also be made about the nature of the studied star based on the photometric results. Taking the intrinsic colors (H − K)0 of different classes of stars from Wegner (2014, 2015), we compare them with the (H − K) color of the counterpart determined from the NOT observations. From a simple relation E(H − K) = (H − K) − (H − K)0, we can find an extinction correction for each class of stars to correspond to the measured color of the source. Assuming a standard extinction law (Cardelli et al. 1989) expected in this sky region, we can transform each E(H − K) into AK. At the same time, comparing absolute magnitudes in the K band of the same stars (Wegner 2000, 2006, 2007) with the measured magnitude of the source in the K band (taking into account AK), we can estimate a probable distance to each class of stars from a relation 5–5 log10 D = MK,abs − KNOT + AK.

The results of such estimations for different classes of stars are presented in Figure 10. From this diagram, it is not possible to unambiguously determine the class of the companion, but we can get some restrictions on the extinction magnitude toward the source. In particular, for OB giants or supergiants, the extinction AK toward XTE J1858+034 should be ~3.1–3.4; for red giant stars, AK ≃ 2.6–3.0; and for main-sequence stars, AK is somewhere between these values. In particular, if we assume that the optical counterpart of XTE J1858+034 is a giant star, it should be located at ~4–14 kpc from the Sun. Note that the above extinction converted into the hydrogen column density NHI via standard relations (Predehl & Schmitt 1995; Güver & Özel 2009) generally agrees with the results obtained from the source X-ray spectrum in the low state.

A significant absorption toward the source can easily explain its nondetection in optical filters at the NOT and with Gaia. The extinction AK ≃ 2.8 corresponds to A₁ ≃ 16 for the standard law. Thus, an expected magnitude of the source in the i filter should be ~30.

At the next step, we compare the observed colors (J − K) and (J − H) of the counterpart with the intrinsic ones of different classes of stars in a similar way as described by Karasev et al. (2012). The red dots in Figure 11 indicate the colors of the different types of stars in the nearest 100 pc from the Sun taken from the Two Micron All Sky Survey (2MASS) catalog and Hipparcos observatory data (van Leeuwen 2007). The interstellar extinction for such nearby stars in the IR filters is negligibly small, so we obtain the desired set of unabsorbed reference stars of different classes. The lines at the bottom indicate the regions of the diagram corresponding to a particular type of star (marked by the letters; see, e.g., Wegner 2014, 2015).

The position of the IR counterpart of XTE J1858+034 (J − H ≃ 3.27 and J − K ≃ 5.04) is far beyond this diagram due to a significant interstellar extinction (see Figure 12). But, by correcting the source’s magnitudes for different extinctions, we
The violet polygon marks the most probable class of stars to be a real counterpart of XTE J1858. The position of the measured colors of the source in the color–color diagram shows that only the red giants of late K or M classes are eligible to be a real companion of XTE J1858+034. At the same time, early classes of giants or supergiants can be excluded according to this diagram.

As was previously shown, if the counterpart of XTE J1858+034 is indeed a red giant star, the magnitude of the absorption toward the source is $A_K \approx (2.6 \pm 3.0)$. Using these values for the extinction correction of the observed colors, we can additionally restrict the class of possible source companions (violet dashed polygon in Figure 11).

Summarizing all of the above, we can conclude that the most likely optical counterpart of the source is a K-M red giant located at a distance of 7–14 kpc. It is worth noting that such a significant distance to the system is supported by the X-ray timing analysis performed by Malacaria et al. (2021), whose estimate is $d \sim 10.9$ kpc.

The same conclusion can be reached using a slightly different approach to the analysis and interpretation of photometric measurements. The $JHK$ photometry of point sources in the $80' \times 80'$ field of view of the NOTCam high-resolution camera in the $J-H/H-K$ and $J-K/J-H$ color–color diagrams is shown in Figure 12. In both diagrams, the intrinsic colors of main-sequence stars are shown as a solid blue curve, while those of giants (dotted pink curve) and supergiants (dotted-dashed pink curve) are taken from Koornneef (1983). Giants and supergiants overlap, but both clearly separate from the main-sequence stars at late spectral types. The reddening vector is plotted for an A0 star as a dashed line based on a standard interstellar extinction law (Cardelli et al. 1989). The target is the circled dot, one of the reddest objects detected in all three filters. We see that the target seems to follow the trace of a highly reddened late-type giant or supergiant, and its location does not fit an early-type reddened star. The photometry clearly supports the spectroscopic suggestion of a K or M giant or supergiant. The intrinsic $H-K$ color is in the small range from 0.12 to 0.35 mag from K0 to M6 stars according to Koornneef (1983) and Wegner (2014). The two extremes give $E(H-K) = (H-K)_\text{int} - (H-K)_\text{obs}$ from 1.42 to 1.65 mag, which translates to extinction estimates of $A_K$ in the range from 2.5 to 2.9 mag. This gives a dereddened $K$-band magnitude in the range from 10.6 to 11.0 mag. The different spectral types have
different absolute K-band magnitudes, resulting in a range of distances from 7 to 14 kpc for K-M giants, while for supergiants, the distance is even larger.

4.3. Previously Proposed Companions

At least two different stars were earlier considered as a possible companion of XTE J1858+034 (Reig et al. 2005; Malacaria et al. 2020). The first star was discussed above and is the only one in the nearby vicinity of XTE J1858+034 (see Figure 6, marked by a plus sign) whose optical spectrum shows Hα emission. Reig et al. (2005) suggested that this object was a Be star and a possible counterpart of XTE J1858+034. It is important to note that the coordinates of this star reported by Reig et al. (2005) are approximately 6° away from another X-ray object, registered by Chandra inside the INTEGRAL/IBIS error circle (marked with the number 2 in Figure 6, coordinates R.A. = 18°58′35″62, decl. = 3°26′10″5; Skiff 2014). We checked Pan-STARRS and Gaia data and found that there is only one optical star coinciding exactly with the Chandra source number 2. Its magnitudes in optical filters are similar to the ones reported by Reig et al. (2005). These facts allow us to suggest that this star and the star reported by Reig et al. (2005) are the same object. The Gaia data indicate that it is located at a distance of ≈200 pc (Bailer-Jones et al. 2018) and has an effective temperature of Teff ≈ 4000 K (Gaia Collaboration et al. 2018). These measurements, as well as the registration of the Hα emission line by Reig et al. (2005), indicate that it can be a nearby cataclysmic variable.

Another optical companion of XTE J1858+034 was considered by Malacaria et al. (2020) from the Gaia catalog as the closest star to the nominal source position known at that moment (marked by a cross in Figure 7). Based on the above analysis, this hypothesis can now be firmly ruled out as well.

5. Conclusion

In this work, we present the results of the spectral and temporal analysis of a poorly studied XRP, XTE J1858+034, performed in a broad range of energies and mass accretion rates. The spectrum of the source obtained with the NuSTAR observatory during an outburst in 2019 revealed the presence of a cyclotron absorption line in the energy spectrum at Eq ≈ 48 keV that allowed us to estimate the NS magnetic field strength as 5.2 × 1012 G. The spectral properties of XTE J1858+034 observed by the XMM-Newton and Chandra observatories in the quiescent state point to ongoing accretion in this state, which we interpreted as accretion from the cold (low-ionization) accretion disk.

Chandra data allowed us to obtain the precise localization of XTE J1858+034 for the first time. Observations at the NOT revealed only one potential near-IR companion of the pulsar. The spectral properties of the counterpart point to the red giant star located at 7–14 kpc, suggesting that the system is likely a symbiotic binary hosting an XRP rather than a Be X-ray binary, as previously proposed. This distance agrees well with estimates obtained from the timing properties of the pulsar (Malacaria et al. 2021).

This work was supported by grant 19-12-00423 of the Russian Science Foundation. Studies partially based on observations made with the Nordic Optical Telescope, owned in collaboration by the University of Turku and Aarhus University and operated jointly by Aarhus University, the University of Turku, and the University of Oslo, representing Denmark, Finland, and Norway, the University of Iceland and Stockholm University at the Observatorio del Roque de los Muchachos, La Palma, Spain, of the Instituto de Astrofísica de Canarias.

References

Anders, E., & Grevesse, N. 1989, GeCoA, 53, 197
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Mantelet, G., & Andrae, R. 2018, AJ, 156, 58
Basko, M. M., & Sunyaev, R. A. 1975, A&A, 42, 311
Boldin, P. A., Tsygankov, S. S., & Lutovinov, A. A. 2013, AstL, 39, 375
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Daugherty, J. K., & Harding, A. K. 1986, ApJ, 309, 362
Davies, B., Figer, D. F., Kudritzki, R.-P., et al. 2007, ApJ, 671, 781
Djupvik, A. A., & Andersen, I. 2010, in Highlights of Spanish Astrophysics V, ed. J. Diego et al. (Berlin: Springer), 211
Doroshenko, V., Tsygankov, S. S., Mushtukov, A. A., et al. 2017, MNRAS, 466, 2143
Doroshenko, V. A., Doroshenko, R. F., Postnov, K. A., Cherepashchuk, A. M., & Tsygankov, S. S. 2008, ARep, 52, 138
Filippova, E. V., Tsygankov, S. S., Lutovinov, A. A., & Sunyaev, R. A. 2005, AstL, 31, 729
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A1
Garmire, G. P., Bautz, M. W., Ford, P. G., & Nousek, J. A. 2003, Proc. SPIE, 4851, 28
Güver, T., & Özel, F. 2009, MNRAS, 400, 2050
Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103
Herold, H. 1979, PhRvD, 19, 2868
Karasev, D. I., Lutovinov, A. A., Revnivtsev, M. G., & Krivonos, R. A. 2012, AstL, 38, 629
Koornneef, J. 1983, A&A, 200, 247
Krimm, H. A., Holland, S. T., Corbet, R. H. D., et al. 2013, ApJS, 209, 14
Leahy, D. A. 1987, A&A, 180, 275
Lutovinov, A. A., & Tsygankov, S. S. 2009, AstL, 35, 433
Malacaria, C., Jenke, P., Roberts, O. J., et al. 2020, ApJ, 896, 90
Malacaria, C., Kretschmar, P., Madsen, K. K., et al. 2021, ApJ, 909, 153
Marshall, F. E., Chakrabarty, D., & Finger, M. H. 1998, IAUC, 6828, 2
Molkov, S. V., Cherepashchuk, A. M., Revnivtsev, M. G., et al. 2004, ATel, 274, 1
Mushtukov, A. A., Suleimanov, V. F., Tsygankov, S. S., & Poutanen, J. 2015a, MNRAS, 447, 1847
Mushtukov, A. A., Tsygankov, S. S., Serber, A. V., Suleimanov, V. F., & Poutanen, J. 2015b, MNRAS, 454, 2714
Nakajima, M., Mihara, T., & Makishima, K. 2010, ApJ, 710, 1755
Nakajima, M., Negoro, H., Kurogi, K., et al. 2019, ATel, 13217, 1
Paul, B., & Rao, A. R. 1998, A&A, 337, 815
Predehl, P., & Schmitt, J. H. M. M. 1995, A&A, 293, 889
Reig, P., Negueruela, I., Papamastorakis, G., Manousakis, A., & Kougentakis, T. 2005, A&A, 440, 637
Remillard, R., Levine, A., Takahira, T., et al. 1998, IAUC, 6826, 2
Skiff, B. A. 2014, yCat, 1, 2023
Staubert, R., Trümper, J., Kendziorra, E., et al. 2019, A&A, 622, A61
Takeshima, T., Corbet, R. H. D., Marshall, F. E., Swank, J., & Chakrabarty, D. 1998, IAUC, 6826, 1
Tsygankov, S. S., Mushtukov, A. A., Suleimanov, V. F., et al. 2017a, A&A, 608, A17
Tsygankov, S. S., Wijnands, R., Lutovinov, A. A., Degenaar, N., & Poutanen, J. 2017b, MNRAS, 470, 126
van Leeuwen, F. 2007, A&A, 474, 653

Wachter, K., Leach, R., & Kellogg, E. 1979, ApJ, 230, 274
Wallace, L., & Hinkle, K. 1997, ApJS, 111, 445
Wegner, W. 2000, MNRAS, 319, 771
Wegner, W. 2006, MNRAS, 371, 185
Wegner, W. 2007, MNRAS, 374, 1549
Wegner, W. 2014, AcA, 64, 261
Wegner, W. 2015, AN, 336, 159