# ULTRA LUMINOUS X-RAY SOURCES - NEW DISTANCE INDICATORS?

Agata Różańska<sup>1</sup>, Karol Bresler<sup>2</sup>, Bartosz Bełdycki<sup>1</sup>, Jerzy Madej<sup>3</sup> and Tek P. Adhikari<sup>1</sup>

# **ABSTRACT**

This paper presents X-ray broad-band spectral observations of the Ultra Luminous X-ray source (ULXs) NGC7793 P13 obtained by *NuSTAR* and *XMM-Newton* satellites. Reduced data were successfully fitted with only single spectral emission component from non-spherical system: neutron star plus accretion disk. We obtained the very good fit with the reduced  $\chi^2$  per degree of freedom equal 1.08. Furthermore, the normalization of our model constrains the distance to the source. The resulting distance to the ULX source P13,  $D = 3.41^{+0.11}_{-0.10}$  Mpc, is with perfect agreement with the distance determination based on the Cepheid method to the hosting galaxy NGC7793. Our result shows that the ULX sources may contain central hot neutron star and the accretion disk. When the outgoing emission is computed by integration over the whole non-spherical system and successfully fitted to the data, then the resulting model normalization is the direct distance indicator.

Keywords: accretion,accretion disks — stars:neutron — X-rays:general

# 1. INTRODUCTION

Recent observations suggest that some Ultra Luminous X-ray (ULX) sources contain neutron star in their centers, since a typical coherent pulsation from magnetized pulsar was detected in case of: M82X-1 and M82X-2 (Bachetti et al. 2014), and NGC7793 P13 (Fürst et al. 2016; Israel et al. 2017). The fact that mass of the central object may equal 1.4 solar masses particularly implies that the accretion disk has to be highly super Eddington in those sources. Such a consequence directly results from the large values of the observed X-ray luminosities from those systems, which always exceed the theoretical maximum for spherical infall onto a stellar-mass black hole (Roberts 2007; Liu et al. 2013).

Furthermore, the broad-band spectra of those sources obtained simultaneously by *XMM-Newton* and *NuSTAR* X-ray satellites, always are too broad to be fitted by only one multitemperature disk component. The second spectral component as thermal Comptonization or black body from the neutron star surface is needed to fully explain the spectral shape (Walton et al. 2013, 2017).

Theoretical explanation for the broad spectral shape was given by Różańska et al. (2017) in the case of low mass X-ray binaries (LMXB). As is well known the observed flux from a spherically symmetric star is proportional to the flux emitted locally from the unit surface of the source, and is proportional to the square of the star radius divided by the square distance (Mihalas 1978). Instead, in case of any non-spherical geometry of emitting region we need to carefully integrate the specific intensity over the solid angle subtended by the source.

We performed such computations for a neutron star with the accretions disk (Różańska et al. 2017), and obtained broad spectrum of the system in the one model component. Our model contains emission from both regions with the effects of mutual attenuation which gives the proper model normalization. Final spectrum depends on the viewing angle in the whole energy range and for the assumed emitting surface it is proportional to the inverse square distance.

In this paper, we reduce archival broad-band data of NGC77 P13 (hereafter P13), the ULX source which reaches luminosities of  $L_{\rm X} \sim 10^{40}$  erg s<sup>-1</sup>. This system is one of the three neutron star ULXs known at present. The observations were taken on 2016 with *XMM-Newton* (Jansen et al. 2001) and *NuSTAR* (Harrison et al. 2013) telescopes simultaneously. Spectral analysis was done by Walton et al. (2017), where their final model contained several components In this paper we show, that our single model of non-spherical emission from a neutron star with the standard accretion disk fits the broad-band spectrum of P13 perfectly.

Organization of this paper is as follows: Sec. 2 and 3 present the model description and parameters, respectively. Sec. 4 briefly introduces observational properties of the source P13. Data reduction process is described in Sec. 5, and the final results of our fitting procedure are presented in Sec. 6. Sec. 7 is devoted to summarize the final conclusions.

# 2. SINGLE MODEL OF EMISSION FOR ULXS

We assume that ULX source is a non-spherical system containing neutron star with the accretion disk around it. For

<sup>&</sup>lt;sup>1</sup>Copernicus Astronomical Center, Bartycka 18, 00-716 Warszawa, Poland, agata@camk.edu.pl

<sup>&</sup>lt;sup>2</sup>Warsaw University of Technology, Plac Politechniki 1, 00-661 Warszawa, Poland

<sup>&</sup>lt;sup>3</sup> Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00-478, Warszawa, Poland

such object geometry, the infinitesimal energy  $d\mathcal{F}_{\nu}$  measured by a distant observer is defined as:

$$d\mathcal{F}_{v} = I_{v}d\omega,\tag{1}$$

where  $d\omega$  is a solid angle in steradian [sr] (Mihalas 1978). This formula is applicable for the flat space, as we assume in this paper. In case when the emitter is located close to black hole, both general and special relativistic corrections should be taken into account as in Fabian et al. (1989, Eq. A4).

Integrating Eq. 1 over the solid angle subtended by the source, we obtained energy dependent intensity:  $\mathcal{F}_{\nu}$  as seen by the observer. This quantity diminishes with the increasing distance and it is not an intrinsic property of the source.

In the case of emission from the whole system i.e. neutron star with the accretion disk around it, we have the contribution from different emitting parts (for details see: Różańska et al. 2017) and the final observed energy dependent intensity directed to the observer is computed analytically as:

$$\mathcal{F}_{\nu,\text{All}} = \pi \left(\frac{R_{\text{NS}}}{D}\right)^{2} \left[ \int_{0}^{1} I_{\nu} \mu d\mu + \int_{\cos \theta'}^{1} I_{\nu} \mu d\mu \right]$$

$$+ \frac{2}{D^{2}} \left[ \int_{0}^{R_{\text{NS}}} I_{\nu} \sin \theta' \sqrt{R_{\text{NS}}^{2} - x^{2}} dx \right]$$

$$- \int_{0}^{R_{\text{NS}} \sin \theta'} I_{\nu} \sqrt{R_{\text{NS}}^{2} \sin^{2} \theta' - x^{2}} dx$$

$$+ \pi \frac{\sin \theta'}{D^{2}} \left( \int_{R_{\text{in}}}^{R_{\text{out}}} I_{\nu} R dR + \int_{R_{\text{boost}}}^{R_{\text{out}}} I_{\nu} R dR \right), \qquad (2)$$

where  $R_{\rm NS}$  is the neutron star radius, D - the distance to the system, and  $I_{\nu}$  - the specific intensity emitted from the source surface towards the observer. Several other variables denote respectively:  $\mu = \cos\theta$ , where  $\theta$  is the angle between direction of the light beam and the normal to the neutron star surface,  $\theta'$  is viewing angle related to the disk inclination angle as  $i = 90^{\circ} - \theta'$  (see Fig. 3 in Różańska et al. (2017) for illustration ), and x is the variable of integration over the source surface projected on the sky.

First two parts of above equation correspond to the emission from the neutron star surface taking into account the attenuation by the disk, while second two parts describe the disk emission with eventual attenuation by the neutron star. Due to mutual attenuation one part of the disk is integrated over radius from the innermost stable orbit  $R_{\rm in}$  all the way up to the outer radius  $R_{\rm out}$ , while the second part of the disk from  $R_{\rm boost} = R_{\rm NS}/\sin\theta'$  up to the outer radius  $R_{\rm out}$ .  $R_{\rm boost}$  the radius up to which neutron star attenuates the inner part of an accretion disk.

The above formula was derived analytically in our recent paper by Różańska et al. (2017), where we have demonstrated that the broad-band emitted spectrum from a nonspherical system depends on the viewing angle, since then both: disk emission and neutron star emission change with angle. This particular geometry of emission is exceptional

since it has cylindrical symmetry. For more complicated source derivation of the above equation should be done individually, depending on geometry.

We assume, that the neutron star radiation is isotropic and equals the black body intensity at the given effective temperature  $I_{\nu}=B_{\nu}(T_{\rm eff,NS})$ . Furthermore, we assume that the emission at different disk radii equals to the local Planck function  $I_{\nu}=B_{\nu}(T_{\rm eff}(R))$ , with effective temperature given by standard Shakura & Sunyaev (1973) formula:  $\sigma T_{\rm eff}^4(R)=3GM\dot{M}/8\pi R^3(1-(R_{\rm in}/R)^{1/2})$ , where  $\sigma$  is the Stefan-Boltzman constant, G is the gravitational constant, M - mass of the central object and  $\dot{M}$  - disk accretion rate. We note here, that our model is useful for systems where the angle dependent specific intensity is given as the results of the radiative transfer calculations (Madej 1989, 1991; Hubeny et al. 2001; Davis et al. 2005; Różańska et al. 2011). We plan to implement atmospheric models in the future work.

## 3. MODEL PARAMETERS

For the purpose to compare our model to the observed X-ray spectrum of ULX source P13, we constructed the grid of models for arbitrarily assumed parameters. The non-rotating neutron star has a canonical mass 1.4  $M_{\odot}$ , radius 12 km, and 11 various effective temperatures, ranging from  $2 \times 10^6$  K up to  $4 \times 10^7$  K. The disk local emission was computed assuming 11 accretion rates from  $8 \times 10^{-4}$  up to  $8 \times 10^{-1}$  in the unit of the Eddington accretion rate, with accretion efficiency equal 0.08 (Schwarzschild metric).

For each disk model, we calculated multi-black body spectrum from  $R_{\rm in}$  to  $R_{\rm out}$  in the range 3-1000  $R_{\rm Schw}$ , where the  $R_{\rm Schw}=2GM_{\rm NS}/c^2$ . The inner disk radius can change due to the: large value of magnetic field, strong boundary layer, and when the relativistic corrections are taken into account. We plan to include them in the future paper together with full ray tracing procedure. The outer disk radius depends on the secondary object, and resulting size of the Roche lobe. We have checked that for the typical mass of the secondary less than the solar mass, there is enough space for the disk of a radius up to  $1000~R_{\rm Schw}$  (Paczyński 1971). Since the outer disk regions emit in optical band, its value does not influence our results, and we keep it constant within this paper.

The grid of  $\theta'$  angles spans from  $10^\circ$  up to  $90^\circ$ . The lowest value of this angle corresponds to the almost "edge on" disk, whereas the highest value to "face on" disk. We use the lowest value of  $\theta'=10^\circ$ , since for smaller viewing angles the disk geometrical thickness is large enough to obscure neutron star completely. Furthermore, in Shakura & Sunyaev (1973) model, the disk height increases with radius, and for the disk seen "edge on", we observe only the disk rim.

Our model normalized by the distance of D = 10 kpc, was prepared as a table model in the FITS (Flexible Image Transport System) format (Wells et al. 1981), and for the purpose of this paper we named it lmxb. Final table of emission from

the system containing neutron star with the accretion disk is parametrized by four parameters which will be determined during fitting procedure: neutron star effective temperature,  $T_{\rm eff,NS}$ , disk accretion rate  $\dot{m}$  in units of Eddington accretion rate, viewing angle  $\theta'$ , and normalization N. Since the normalization of our model is proportional to  $1/D^2$ , the value of this normalization which comes out from the fitting procedure is the direct indicator of the distance to the system. Therefore, the distance to the source equals  $10/\sqrt{N}$  kpc. Below we show that in case of P13 the distance derived from our fitting is in excellent agreement with independent distance measurement.

# 4. NGC7793 P13

P13 is a variable ULX source, that has originally been proposed to harbour a stellar black hole of a mass less than 15  $M_{\odot}$  (Motch et al. 2014). However, recent studies by Fürst et al. (2016); Israel et al. (2017); Walton et al. (2017) have discovered that P13 actually hosts an accreting neutron star with the spin period of 0.42 s. The source is a part of the binary system, where it circulates around B91a star of 18-23  $M_{\odot}$ , with the period of 64 days (Motch et al. 2014).

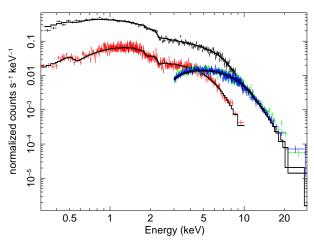
Previously, P13 has been reported to reach luminosities from  $\sim 2 \times 10^{39}$  detected in 1979 by *Einstein* satelite up to  $\sim 10^{40}$  erg s<sup>-1</sup> reported recently with join *XMM-Newton* and *NuSTAR* data by Walton et al. (2017). The source is rather unobscured with galactic warm absorption value:  $N_{\rm H} = 9.60 \pm 0.01 \times 10^{20}$  cm<sup>-2</sup> (Israel et al. 2017). On the other hand Walton et al. (2017) in their paper divided this absorption between galactic absorption with the value of neutral hydrogen estimated towards the object on  $N_{\rm H} = 1.2 \times 10^{20}$  cm<sup>-2</sup> (Kalberla et al. 2005), and intrinsic source absorption resulting from the fit :  $N_{\rm H} = 8 \pm 1 \times 10^{20}$  cm<sup>-2</sup>.

P13 is located in NGC7793 galaxy which is a part of Sculptor Group. The first distance measurement to the source was done by Karachentsev et al. (2003) as a distance to the galaxy itself and was estimated to be  $3.91\pm0.41$  Mpc. Futher distance derivation was done within ARAUCARIA project (Gieren et al. 2005) where for the first time Cepheid Variables were detected in the Sculptor Group. Cepheids distance to the spiral galaxy NGC7793 was found to be  $3.4\pm0.17$  Mpc (Pietrzyński et al. 2010).

# 5. OBSERVATIONS AND DATA REDUCTION

In this work we made use of coordinated *NuSTAR* (OBSID 80201010002) and *XMM-Newton* (OBSID 0781800101) observations of NGC7793 P13. Both observation were taken on 2016-05-20, and their exposure times were: 118 ks for *NuSTAR* and 22/46 ks for EPIC-pn/EPIC-MOS cameras on the board of *XMM-Newton* X-ray telescope. These observations have been already analyzed by Walton et al. (2017) where spectral fitting was done using several spectral components to account for spectral broadening. In this paper we show that the observed spectrum of P13 can be well fitted by

### data and folded model



**Figure 1**. Normalized count from all detectors used in our spectral fitting analysis. Black and red crosses correspond to the *XMM-Newton* detectors EPIC-pn and EPIC-MOS. Green and blue crosses are data from *NuSTAR* FPMA and FPMB respectively. Black solid line is the best fitted model.

the single model (Sec. 2) multiplied by galactic absorption.

We reduced the NuSTAR data from both focal plane modules, FPMA and FPMB, by using NuSTAR Data Analysis Software in accordance to guidelines provided in the NuS-TAR Data Analysis Software Guide (v1.9.2)<sup>1</sup>. Calibration files were taken from the actual database CALDB v20170817 throughout the whole process. NUPIPELINE tool was used in order to produce filtered event files, with standard filtering applied. We utilized NUPRODUCTS tool to extract source products and instrumental response files form circular regions of radius 60". Background products were obtained from four times larger regions located on the same detector chip as P13. Besides the basic so called *science* data we also included spacecraft science data following the guideline outlined in NuSTAR Data Analysis Software Guide (see also Walton et al. 2016). Therefore we were able to increase our exposure time by approximately 10% and maximazie the signal-to-noise (S/N) ratio. Additional data obtained by this action were merged with standard stientific data by runnig FTOOLS task ADDASCASPEC. Final spectra, averaged over exposure time, were binned to at least 20 counts per energy bin for the purpose of data fitting process. The extracted normalized counts are presented in Fig. 1 with green and blue colors for FPMA and FPMB respectively.

The *XMM-Newton* data were reduced with the *XMM-Newton Science Analysis System* (SAS) v16.0.0<sup>2</sup>, following standard guidelines outlined in the science analysis threads. We generated the calibrated and concatenated event lists by running EPCHAIN task for EPIC-pn and EMCHAIN task

<sup>&</sup>lt;sup>1</sup> https://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar\_swguide.pdf

<sup>&</sup>lt;sup>2</sup> https://www.cosmos.esa.int/web/xmm-newton/sas

**Table 1**. Parameters from fitting the P13 data with *tbnew\*lmxb* model. The meaning of fitted parameters is described in Sec. 3.

Model	Parameter	Value	Unit
tbnew	$N_{ m H}$	$4.77^{+0.45}_{-0.44} \times 10^{20}$	cm <sup>-2</sup>
lmxb	$T_{ m eff,NS}$	$1.819 \pm 0.025 \times 10^7$	K
lmxb	m	$0.707^{+0.072}_{-0.097}$	$\dot{m}_{ m Edd}$
lmxb	heta'	$10 \pm 6.59$	deg
lmxb	N	$8.62 \pm 0.54 \times 10^{-6}$	_

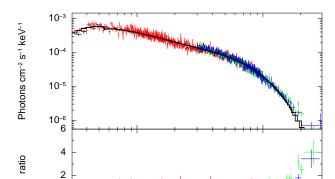
for both EPIC-MOS modules. Next, we created an event file and then subjected it to filtering for background flaring with the help of SAS tasks evselect and tabtigen. To produce final event file with spectrum, the source products were extracted from circular regions of radius 36" and background products were extracted from nine times larger region on the same CCD chip. All regions were extracted in the way to avoid the CCD borders. In evselect, we used the filters FLAG== 0 PATTERN< 4 for EPIC-pn and FLAG== 0 PATTERN< 12 for the EPIC-MOS cameras. The appropriate response files and ancillary files were generated using the SAS commands rmfgen and arfgen respectively. Lastly, we combined the spectra form both EPIC-MOS detectors by running FTOOLS task ADDASCASPEC. Final EPIC-pn spectrum was be binned to at least 10 counts per energy bin, while spectra from both MOS cameras were binned to at least 20 counts per energy bin for data fitting process. The extracted normalized counts are presented in Fig. 1 with black and red colours for EPIC-pn and EPIC-MOS respectively.

# 6. SPECTRAL ANALYSIS

We performed spectral fitting for the P13 source with a single model of emission presented in Sec 2. The model is parametrized in the most simple way assuming multi-temperature standard accretion disk and the black body emission from a neutron star as described in Sec 3. We used XSPEC fitting package, version 12.9.0<sup>3</sup> for further data analysis.

We fitted all data simultaneously using single model *lmxb* multiplied by galactic absorption standard xspec model *tb-new*. In the warm absorption model we froze all values of metal abundances and allow only hydrogen column density to be fitted. Tab. 2 presents all fitted parameters. All uncertainties are given at the 90% of confidence level.

The quality of fit is excellent since the data are very good giving 1245 degrees of freedom (dof). The reduced statistics is  $\chi^2/dof = 1.08$  indicating that our single model of emission from the non-spherical system perfectly agrees with P13 data, which we illustrate at Fig. 2. Unfolded spectrum from all detectors is broad and correctly agrees with the model up to 20 keV. There is a small deviation for higher energies re-



Unfolded Spectrum

Energy (keV)

10

**Figure 2.** Upper panel shows unfolded photon spectrum from all detectors used in our spectral fitting analysis, while lower panel presents the ratio i.e. data divided by model. Black and red crosses correspond to the *XMM-Newton* detectors EPIC-pn and EPIC-MOS. Green and blue crosses are data from *NuSTAR* FPMA and FPMB respectively. Black solid line on the upper panel is the best fitted model.

0

0.5

sulting in the value of ratio (data/model) reaching 4, but this feature is always present in ULX sources broad-band spectral analysis. Even in the case of multi-component spectral fitting of P13 by Walton et al. (2017), this ratio is between 2 and 3.5. This fact may suggest that the hard energy tail is still not well detected by us and furthermore not well modeled. Our single model does not exclude, that hard X-ray corona may form in the innermost part of the disk. Nevertheless, in this paper we aim to show how the observed spectral broadening in the X-ray energy domain can be explained by the emission from non-spherical objects.

**Table 2.** Results from fitting the P13 data with *tbnew\*lmxb* model. Unabsorbed fluxes are calculated using standard xspec command. The distance to the source is determined from the normalization of the model. Finally, the X-ray luminosity is computed.

Parameter	Value	Unit
$\chi^2/dof$	1344/1245	_
$F_{\rm X}(2\text{-}10~{\rm keV})$	$4.36 \times 10^{-12}$	$erg{\cdot}s^{-1}{\cdot}cm^{-2}$
$F_{\rm X}(0.3-30~{\rm keV})$	$6.83 \times 10^{-12}$	$erg{\cdot}s^{-1}{\cdot}cm^{-2}$
$D = 10/\sqrt{N}$	$3.41^{+0.11}_{-0.10}$	Mpc
$L_{\rm X}(0.3-30~{\rm keV})$	$9.59 \times 10^{39}$	$erg \cdot s^{-1}$

The fitted value of galactic absorption is consistent with previous estimations described in Sec. 4. Since this value is quite low it does not affect other parameters. The neutron star effective temperature is high, giving rise to the hard energy bump in the observed spectrum. It is clearly seen in the unfolded energy spectrum plotted in  $E*F_E$  versus E at Fig. 3.

The resulting inclination angle suggests that the whole system is observed edge on, and the neutron star is strongly attenuated by the accretion disk. In case of the P13 source

<sup>&</sup>lt;sup>3</sup> https://heasarc.gsfc.nasa.gov/xanadu/xspec/

# keV<sup>2</sup> (Photons cm<sup>-2</sup> s<sup>-1</sup> keV<sup>-1</sup>) 10<sup>-4</sup> 10<sup>-3</sup> 10 20 Energy (keV)

Unfolded Spectrum

**Figure 3**. Unfolded energy spectrum from all detectors used in our spectral fitting analysis.  $E * F_{\rm E}$  quantity is plotted to show the maximum emission from hard energy tail which is associated with the emission from hot neutron star atmosphere. Black and red crosses correspond to the *XMM-Newton* detectors EPIC-pn and EPIC-MOS. Green and blue crosses are data from *NuSTAR* FPMA and FPMB respectively. Black solid line is the best fitted model.

considered in this paper, the integration over such emitting area fully explains the shape of X-ray observed spectrum.

Since the emission from non-spherical region fits observations, we can calculate the distance to the P13 from the model normalization. The obtained value  $D = 3.41^{+0.11}_{-0.10}$  Mpc agrees with two earlier distance estimations to the Sculptor Group being  $3.91 \pm 0.41$  Mpc (Karachentsev et al. 2003), and to the host galaxy NGC7793 from Cepheid method –  $3.4\pm0.17$  Mpc (Pietrzyński et al. 2010).

Such agreement strongly suggests that our model is correct and the proper emission from several regions with mutual attenuation should be taken account during broad-band data analysis of accreting systems.

# 7. DISCUSSION

In this paper we showed, that the broad-band spectrum of ULX source P13 in NGC7793 galaxy, is well fitted by a single model component. The model is built by proper integration over non-spherical and non-uniform emitting region. The best fitted model indicates that P13 is the hot neutron star  $T_{\rm eff,NS}=1.819\pm0.025\times10^7$  K, with the hot accretion disk  $\dot{m}=0.707^{+0.072}_{-0.097}$  in units of Eddington accretion rate. The whole system is strongly inclined, seen almost edge on.

Our results clearly show that the integration over true intensity emitted by a given surface should be applied to explain emission from non-spherical systems. When this was done, we obtain a new possibility to explain broad-band spectra by a single model component. Furthermore, we can calculate the distance to the source from the normalization of such a single model. We derived the distance to P13,  $D = 3.41^{+0.11}_{-0.10}$  Mpc, which is in very good agreement with previous estimations (as discussed in Sec. 6).

There exists a more general result of our analysis. Any additional soft X-ray bump, which is very often observed in X-ray spectra of accreting objects is usually fitted by separate model components, either disk or black-body. Here, we have proven that this problem can be solved, when we integrate emission over the disk with hot inner source. Such central hot source may be for instance a neutron star or a hot corona and may be partially attenuated by the disk.

# **ACKNOWLEDGMENTS**

This research was supported by Polish National Science Center grants No. 2015/17/B/ST9/03422, 2015/18/M/ST9/00541, and 2016/21/N/ST9/03311. This research has made use of data obtained with *NuSTAR*, a project led by Caltech, funded by NASA and managed by NASA/JPL, and has utilized the NUSTARDAS software package, jointly developed by the ASDC (Italy) and Caltech (USA). This work has also made use of data obtained with *XMM-Newton* directly funded by ESA Member States.

# REFERENCES

Bachetti, M., Harrison, F. A., Walton, D. J., et al. 2014, Nature, 514, 202
Davis, S. W., Blaes, O. M., Hubeny, I., & Turner, N. J. 2005, ApJ, 621, 372
Fabian, A. C., Rees, M. J., Stella, L., & White, N. E. 1989, MNRAS, 238, 729

Fürst, F., Walton, D. J., Harrison, F. A., et al. 2016, ApJ, 831, L14 Gieren, W., Pietrzynski, G., Bresolin, F., et al. 2005, The Messenger, 121,

Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103
Hubeny, I., Blaes, O., Krolik, J. H., & Agol, E. 2001, ApJ, 559, 680
Israel, G. L., Papitto, A., Esposito, P., et al. 2017, MNRAS, 466, L48
Jansen, F., Lumb, D., Altieri, B., et al. 2001, A&A, 365, L1
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775

Karachentsev, I. D., Grebel, E. K., Sharina, M. E., et al. 2003, A&A, 404, 93

Liu, J.-F., Bregman, J. N., Bai, Y., Justham, S., & Crowther, P. 2013, Nature, 503, 500 Madej, J. 1989, ApJ, 339, 386

-.. 1991, ApJ, 376, 161

Mihalas, D. 1978, Stellar atmospheres /2nd edition/ (San Francisco, W. H. Freeman and Co., p. 650)

Motch, C., Pakull, M. W., Soria, R., Grisé, F., & Pietrzyński, G. 2014, Nature, 514, 198

Paczyński, B. 1971, ARA&A, 9, 183

Pietrzyński, G., Gieren, W., Hamuy, M., et al. 2010, AJ, 140, 1475 Roberts, T. P. 2007, Ap&SS, 311, 203

Różańska, A., Bełdycki, B., Madej, J., Adhikari, T. P., & You, B. 2017, Acta Astron., 67, 51

Różańska, A., Madej, J., Konorski, P., & Sądowski, A. 2011, A&A, 527, A47

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337

Walton, D. J., Fuerst, F., Harrison, F., et al. 2013, ApJ, 779, 148

Walton, D. J., Tomsick, J. A., Madsen, K. K., et al. 2016, ApJ, 826, 87

Walton, D. J., Fuerst, F., Harrison, F. A., et al. 2017, ArXiv e-prints, arXiv:1705.10297

Wells, D. C., Greisen, E. W., & Harten, R. H. 1981, A&AS, 44, 363