Insight-HXMT, NuSTAR, and INTEGRAL Data Show Disk Truncation in the Hard State of the Black Hole X-Ray Binary MAXI J1820+070

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Abstract

We study X-ray and soft gamma-ray spectra from the hard state of the accreting black hole binary MAXI J1820+070. We perform an analysis of joint spectra from HXMT, NuSTAR, and INTEGRAL. We find an overall agreement between the spectra from all three satellites. Satisfactory fits to the data require substantial spectral complexity, with our models including two Comptonization regions and their associated disk reflection, a disk blackbody, and a narrow Fe Kα line. Our fits confirm the presence of the truncation of the reflecting optically thick disk at least at >10 gravitational radii. However, we find that the HXMT data alone cannot significantly constrain the disk inner radii.

1. Introduction

The knowledge of the geometry of accretion flows onto black holes (BHs) is crucial for understanding the physics of accretion. While there is largely a consensus that the standard disk model of a geometrically thin, optically thick accretion disk (Novikov & Thorne 1973; Shakura & Sunyaev 1973) extending down to the innermost stable circular orbit (ISCO) applies to the soft spectral state of accreting BH binaries, there is an ongoing controversy regarding the geometry of accretion in the hard spectral state. The dominant paradigm for a number of years, that the inner disk is truncated and replaced by a hot flow (e.g., Done et al. 2007), has been questioned in papers claiming the disk extends down almost to the ISCO also in the hard state; see Bambi et al. (2021) for a recent review.

Here we address this question for MAXI J1820+070, a bright transient accreting BH binary whose outburst was discovered in 2018 (Kawamuro et al. 2018; Tucker et al. 2018). The presence of a disk extending almost to the ISCO in its hard state was advocated in Kara et al. (2019), Buisson et al. (2019), and Wang et al. (2021). On the other hand, studies by Wang et al. (2020), Axelsson & Veledina (2021), Dzielak et al. (2021), De Marco et al. (2021), Marino et al. (2021), Zdziarski et al. (2021b, 2021c, hereafter Z21c), and Kawamura et al. (2022) found the disk to be significantly truncated over various stages of the hard state.

You et al. (2021, hereafter Y21) analyzed broad energy spectra (2–200 keV) in the hard state from the Hard X-ray Modulation Telescope (Insight-HXMT; Zhang et al. 2014) for MAXI J1820+070 in the 2018 outburst. It was found that the reflection fraction, defined as the ratio of the coronal flux that illuminates the disk to that emitted outside, showed an overall decrease with the decreasing hardness of the X-ray spectrum.

The latter decrease, in turn, was found (Kara et al. 2019; De Marco et al. 2021) to be strongly correlated with the decreasing time lag of soft X-rays with respect to hard ones observed by the Neutron Star Interior Composition Explorer (NICER; Gendreau et al. 2016). This effect was interpreted by Y21 as indicating that the corona is relativistically outflowing, with the outflow velocity increasing with the decreasing coronal scale height. However, the spectral fits of Insight-HXMT alone cannot put constraints on the inner radius of the disk. Here we follow up on the studies of Y21 and Z21c and combine the data from Insight-HXMT used in Y21 with those from the Nuclear Spectroscopic Telescope Array (NuSTAR; Harrison et al. 2013), the Spectrometer on INTEGRAL (SPI; Roques et al. 2003), and the INTEGRAL Soft Gamma-Ray Imager (ISGRI; Lebrun et al. 2003) used in Z21c. We apply two different X-ray spectroscopy models to the joint data, with the main goal of estimating the truncation radius of the disk. Also, we estimate other parameters of the X-ray source.

The parameters of the binary relevant to our study are as follows. The distance is \( D \approx 2.96 \pm 0.33 \) kpc based on a radio parallax (Atri et al. 2020) and \( D \leq 3.11 \pm 0.06 \) kpc based on the proper motion of the moving ejecta during the hard-to-soft state transition (Wood et al. 2021). The inclinations of the binary and radio jet are \( i_\text{b} \approx 66^\circ – 81^\circ \) (Torres et al. 2020) and \( i_\text{r} \approx 64^\circ – 5^\circ \) (Wood et al. 2021), respectively, and the BH mass is \( M_\text{BH} \approx (5.95 \pm 0.22)M_\odot / \sin i_\text{b} \) (Torres et al. 2020).

2. Observations and Data Reduction

For our analysis, we have chosen epochs of the hard state of MAXI J1820+070 for which simultaneous data from all of Insight-HXMT, NuSTAR, and INTEGRAL are available. We have found only two such epochs. They are the same as epochs 1 and 2 in Z21c, which analyzed the NuSTAR and INTEGRAL data only. In the current study, we add the corresponding Insight-HXMT spectral data. The two epochs correspond to the beginning of a plateau phase on the count-rate/hardness plot; see Figure 1 of Zdziarski et al. (2021b). As shown in that work...
(see their Table 2), the bolometric luminosity during that part of the plateau phase was almost constant, at approximately 15% of the Eddington luminosity (assuming $D = 3$ kpc and $M = 8 M_\odot$).

The INTEGRAL data (see Table 1) are from SPI and ISGRI, which jointly cover the 23–650 keV range, and are the same as those in Z21c. The analysis of the SPI data is described in Roques & Jourdain (2019). Data reduction and spectral extraction for ISGRI were done using the OSA v. 11.1 software (Courvoisier et al. 2003). The SPI and ISGRI data include 0.5% and 1% systematic errors, respectively.

The data from NuSTAR (3–79 keV) were reduced with HEASOFT v.6.25, the NuSTARDAS pipeline v.1.8.0, and CALDB v.20200912 from the source region of a 60° circle centered on the peak brightness. The data were grouped to the signal-to-noise ratio $\geq 50$ below 69 keV, and no grouping has been applied at higher energies. Following previous spectral studies of the NuSTAR data, e.g., Buisson et al. (2019), we have applied no systematic errors to the data. The data consist of those from two focal plane modules, A and B; see Table 1.

The Insight-HXMT data are those extracted by Y21. The chosen data sets are listed in Table 1. The low-, medium-, and high-energy (LE, ME, and HE) detectors are used in the 2–10, 10–30, and 30–200 keV ranges, respectively. The individual Insight-HXMT data overlapping with those of NuSTAR have been merged, as described in Table 1. The data were grouped according to the recommendation of the Insight-HXMT team. In order to directly study the spectral calibration of the Insight-HXMT detectors, we have applied no systematic errors to these data. See Li et al. (2020) for estimates of the actual systematic errors.

### Table 1

| Epoch | Insight-HXMT ObsID | Start Time | Exp. LE, ME | SPI Start Time | Exp. SPI | NuSTAR ObsID | Start Time | Exp. A |
|-------|---------------------|------------|-------------|----------------|---------|-------------|------------|------|
| 1     | P011466100402–3     | 58,201,514 | 3688, 4049  | 58,201,555     | 13,604  | 90401309008 | 58,201,526 | 3046 |
| 2     | P011466101202–4     | 58,212,203 | 3800, 3859  | 58,212,181     | 28,507  | 90401309012 | 58,212,200 | 12,334 |
|       |                     | 58,212,541 | 5402        | 58,212,606     | 8305    | 58,213,177 | 12,964    |      |

Note. The times are given in MJD, and the exposures are in seconds.

pointed out in Zdziarski et al. (2021b), the harder component may instead be outflowing and forming a slow sheath of the jet. In Z21c, we studied two sets of simultaneous observations of MAXI J1820+070 in the hard state by NuSTAR and INTEGRAL. The joint data covered the 3–650 keV range. Our major finding was that Comptonization by purely thermal electrons was not sufficient to account for the emission at $\geq 100$ keV, while the high-energy spectrum formed a smooth continuation of that at lower energies. The full spectra were then well fitted by the same model as above, except that the hard Comptonization was by hybrid electrons, i.e., Maxwellian with a high-energy tail. The electron temperatures were found to be rather low, $kT_e \approx 10–30$ keV. The truncation radius was found to be relatively high, $R_t \approx 20–30 R_g$. Also, the average spectrum from all NuSTAR and INTEGRAL observations in the hard state was studied. It was similar in shape to those of the two individual observations but with much better statistics at high energies, which allowed a reliable calculation of the rate of $e^+e^-$ pairs. That rate was found to be quite high but balanced by pair annihilation, leading to the equilibrium relative pair density being low, in agreement with the absence of a pair annihilation spectral feature. This was due to the rather large Thomson optical depth of the hard Comptonization cloud, $\tau_T \approx 5$.

We perform spectral fits using XSPEC (Arnaud 1996). The uncertainties given below correspond to the 90% confidence range for a single parameter, $\Delta \chi^2 = +2.71$. In order to assure that some local minima are not missed, we also scan the parameter space using the steppar command of xspec.

### 3. Spectral Fits

Here we further develop the spectral models of Zdziarski et al. (2021b) and Z21c fitted to X-ray and soft $\gamma$-ray data from MAXI J1820+070 in the hard state. In Zdziarski et al. (2021b), we fitted four observations by NuSTAR, which cover the 3–79 keV energy range. We have found that those spectral data require the presence of two different, softer and harder, Comptonization components and two corresponding reflection components, one strongly relativistically blurred and ionized and one weakly blurred and ionized. No disk blackbody component was included. The Comptonization was modeled as by purely thermal electrons. The harder component dominated the broadband X-ray flux in all cases. Our proposed geometry (see Figure 4 in Zdziarski et al. 2021b) was that of a hot flow within the disk inner truncation radius, $R_{in}$, with a large scale height responsible for the harder Comptonization and a coronal flow covering the disk between $R_{in}$ and a transition radius, $R_t$. The softer primary component reflected from the disk underneath the corona, while the harder one reflected from the radii $>R_t$. The truncation radii were found to be in the range of $R_{in} \approx 10–10^2 R_g$, where $R_g$ is the gravitational radius. As pointed out in Zdziarski et al. (2021b), the harder component may instead be outflowing and forming a slow sheath of the jet.

In Z21c, we studied two sets of simultaneous observations of MAXI J1820+070 in the hard state by NuSTAR and INTEGRAL. The joint data covered the 3–650 keV range. Our major finding was that Comptonization by purely thermal electrons was not sufficient to account for the emission at $\geq 100$ keV, while the high-energy spectrum formed a smooth continuation of that at lower energies. The full spectra were then well fitted by the same model as above, except that the hard Comptonization was by hybrid electrons, i.e., Maxwellian with a high-energy tail. The electron temperatures were found to be rather low, $kT_e \approx 10–30$ keV. The truncation radius was found to be relatively high, $R_t \approx 20–30 R_g$. Also, the average spectrum from all NuSTAR and INTEGRAL observations in the hard state was studied. It was similar in shape to those of the two individual observations but with much better statistics at high energies, which allowed a reliable calculation of the rate of $e^+e^-$ pairs. That rate was found to be quite high but balanced by pair annihilation, leading to the equilibrium relative pair density being low, in agreement with the absence of a pair annihilation spectral feature. This was due to the rather large Thomson optical depth of the hard Comptonization cloud, $\tau_T \approx 5$.

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### 3.1. The NuSTAR and INTEGRAL Data Alone

We first refit the NuSTAR and INTEGRAL data alone. We initially fit the data with the same hybrid Comptonization model as in Z21c (where these data are also denoted as epochs 1 and 2). The model includes two Comptonization regions with two corresponding reflection regions; see above and Section 3.1 of Zdziarski et al. (2021b) for a detailed description. In particular, the BH is assumed to be maximally rotating with a dimensionless spin parameter of 0.998, in which case the ISCO radius is at $\approx 1.24 R_g$. That model fits the high-energy data of the SPI and ISGRI very well up to several hundred keV. In the fits, the two reflection zones have very different characteristic ionization parameters, $\lg \xi \sim 3.5$ and $\sim 1.7$, respectively (Zdziarski et al. 2021b; Z21c).

As in Z21c, we allow for a residual uncertainty of the overall slope of the spectral calibration by multiplying the model spectrum by $K e^{-\Delta \Gamma}$, where we fix $K = 1$ and $\Delta \Gamma = 0$ for module A of NuSTAR. The fitted exponent $\Delta \Gamma$ was found in Z21c and here to be relatively small, $\sim 0.01$ for NuSTAR module B and the INTEGRAL spectra. Also, we require the fitted inclination to be within the joint range of those found for
the binary and the jet, 59° ≤ i ≤ 81° (Wood et al. 2021; Torres et al. 2020).

In the model, the soft Comptonization is purely thermal (with a nonthermal electron tail possible but not affecting the parameters; see Z21c), and its incident spectrum and relativistic reflection are modeled using relkerr (Niedźwiecki et al. 2019). The hard Comptonization is hybrid by electrons with a predominantly Maxwellian distribution with a power-law electron tail above a certain energy, modeled with relkerr_bb (Z21c). In both routines, the incident Comptonization spectrum is modeled using compps (Poutanen & Svensson 1996). The temperature of the seed photons is kept at 0.2 keV, following the results of fitting NICER data by Wang et al. (2020). The current version of relkerr_bb has a small increase in the accuracy of the nonthermal tail and an improvement of the mapping of the used reflection spectra of xillver (García & Kallman 2010; García et al. 2018) on the grid of Comptonization spectra with respect to the version used in Z21c. Still, this has only a minor effect on the fitted parameters and \( \chi^2 \). This model yields \( \chi^2 \approx 954/792 \) and 1762/1307 (which are very similar to those in Z21c) for epochs 1 and 2, respectively.

However, since the Insight-HXMT LE data (which we fit below) extend down to 2 keV, we include a disk blackbody component to the model. This accounts for the observed spectral softening at low energies (see Figure 7 in Zdziarski et al. 2021b). We use the diskbb model (Mitsuda et al. 1984). This significantly improves the fits with \( \chi^2 \approx 940/790 \) and 1680/1305 for epochs 1 and 2, respectively.

Also, we add an unblurred reflection to the above model. This is motivated by the maximum radius for which reflection is calculated in either relkerr or relxill being equal to \( 10^3 R_g \). At this radius, there is still a measurable broadening of the Fe K line. We first add a Gaussian Fe Kα line. For epochs 1 and 2, it yields \( \chi^2 \approx 920/789 \) and 1634/1304, respectively; i.e., the fit improvements are significant. We find that the line is required to have a centroid energy of 6.40 keV and a width of \( \leq 1 \) keV (indicating its origin in a cold and neutral medium), which we then fix in the fit. We have then added instead a remote, static reflection using the hreflectntn model (Niedźwiecki et al. 2019) with the same parameters of the electron distribution as the hard hybrid Comptonization (modeled by relkerr_bb) but with the ionization parameter fixed at the minimum value possible in this model of \( \xi = 1 \) erg cm s\(^{-1}\) (i.e., for the remote reflector being nearly neutral). This results in virtually no difference of the fitted parameters and \( \chi^2 \) with respect to the model with a Gaussian line for epoch 2. This is because only the Fe Kα line contributes to the model significantly in hreflectntn. Thus, in order to keep the model as simple as possible, we use a Gaussian component hereafter. Our model is then

\[
\text{plabs * tbabs(diskbb + relkerr + relkerr_bb + gauss).} \tag{1}
\]

Furthermore, Y21 considered a variable irradiation index, \( q \), corresponding to the disk irradiating flux of \( \propto R^{-q} \). In the models above, the standard value (corresponding to either the disk dissipation, Shakura & Sunyaev 1973, or irradiation by a central point source) of \( q = 3 \) was used. However, we find that for the present data, \( q \) is only weakly constrained to \( \geq 2.2 \) for epoch 1, and allowing it to be free does not improve the \( \chi^2 \). For epoch 2, we obtain a similar \( q \approx 3.0^{+1.5}_{-0.8} \) (and no \( \chi^2 \) improvement). Thus, we hereafter keep the fixed \( q = 3 \). Our fitting results for this case are given in Table 2. Following Zdziarski et al. (2021b) and Z21c, we have allowed the values of \( i \) and \( Z_{Fe} \) to be different for the two epochs. The main motivation here is to see the effect of different data sets and models for the fitted values. In our view, X-ray spectral models cannot by themselves be taken as fully reflecting the physical reality. They provide only some approximations, which then can be tested by combining with results from timing and other studies (see, e.g., De Marco et al. 2021). We also note that while the Fe abundance has to remain constant, some changes of the fitted inclinations are possible due to precession and warping of various parts of the reflecting disk.

The results in Table 2 for epoch 2 are relatively similar to those obtained by Z21c without including the disk blackbody and narrow Fe K line components. We can see that the fitted truncation radius decreased, from \( 31_{-3}^{+9} R_g \) to \( 17_{-3}^{+5} R_g \), and the Fe abundance slightly increased. On the other hand, the present fit for epoch 1 gives \( i \approx 59^\circ \), lower than that in Z21c. As noted above, we constrained \( i \) to \( \geq 59^\circ \). When this constraint is relaxed, the best-fit \( i \) still remains at \( 59^\circ \). Then, the Fe abundance has significantly increased to a rather unlikely (at the best-fit) value of \( Z_{Fe} \approx 3.6_{-0.7}^{+0.5} \). This is apparently an artifact of the fitted model. As discussed by García et al. (2018), the reflector density being kept at a fixed low value in the used reflection model may lead to \( Z_{Fe} \) being artificially high in some cases.

We then studied alternative models. For the sake of simplicity, we consider here only epoch 2, which has a much longer exposure than epoch 1; see Table 1. Above, the reflection of the soft components came from an inner part of the disk and was much more strongly ionized than that of the hard components, which came from an outer disk part; see Figure 4 in Zdziarski et al. (2021b). We thus have three alternative possibilities. The reflection of the hard component could still be from an outer part but with a high ionization, or it could be from an inner part with either low or high ionization. We have found that all three possibilities correspond to local minima with the values of \( \chi^2 \) significantly higher than our previous spectral solution, which has the hard component reflecting from an outer part with low ionization (thus representing the global minimum). The values of \( \Delta \chi^2 \) are \( +66, +33, \) and \( +21 \), respectively. Summarizing our investigations above, our chosen hybrid Compton model of broadband spectra is most likely among the considered models based on the \( \chi^2 \) criterion.

On the other hand, the main purpose of this work is to study the Insight-HXMT spectral data (alone and together with those from NuSTAR and INTEGRAL) for this source, whose useful energy range is (as we find below) \( \lesssim 150 \text{ keV} \). Furthermore, we would like to be able to compare our above results, obtained with the relkerr family of models, with those of the relxillCp models (García & Kallman 2010; Dauser et al. 2016; García et al. 2018). Since relxillCp does not have an option to include a nonthermal tail in the electron distribution, we limit the energy range of the fitted data to \( \lesssim 150 \text{ keV} \); this allows us to not include the high-energy electron tail, which was found to be necessary to fit the INTEGRAL data at higher energies. Also, given the structure of relxillCp, we have to consider the variant of that model with two Comptonization zones and the two corresponding reflection regions overlapping rather than adjacent, i.e., with two independent inner reflection radii, in spite of the objections to their physical reality.
Table 2
The Results of Spectral Fitting the NuSTAR+INTEGRAL Data Alone in the 3–560 keV Range

| Component | Parameter | Epoch 1 | Epoch 2 |
|-----------|-----------|---------|---------|
| ISM absorption | $N_{\text{H}}$ [10$^{22}$] cm$^{-2}$ | 59$^{+3}_{-0}$ | 59$^{+3}_{-0}$ |
| Disk | $kT_{\text{in}}$ [keV] | 0.5$^{+0.1}_{-0.1}$ | 0.4$^{+0.1}_{-0.1}$ |
| and a narrow | $N_{\text{disk}}$ [10$^{21}$] | 7$^{+3}_{-0}$ | 10$^{+3}_{-0}$ |
| 6.40 keV line | $N_{\text{Fe K}\alpha}$ [10$^{-3}$] | 4$^{+1}_{-1}$ | 2$^{+1}_{-1}$ |

Table 3
The Results of Spectral Fitting the NuSTAR+INTEGRAL Data Alone in the 3–150 keV Energy Range

| Component | Parameter | Epoch 1 | Epoch 2 |
|-----------|-----------|---------|---------|
| ISM absorption | $N_{\text{H}}$ [10$^{22}$] cm$^{-2}$ | 1.4f | 1.4f |
| Disk | $kT_{\text{in}}$ [keV] | 0.4$^{+0.2}_{-0.1}$ | 0.4$^{+0.1}_{-0.1}$ |
| and a narrow | $N_{\text{disk}}$ [10$^{21}$] | 49$^{+3}_{-3}$ | 13$^{+3}_{-3}$ |
| 6.40 keV line | $N_{\text{Fe K}\alpha}$ [10$^{-3}$] | 4$^{+1}_{-1}$ | 2$^{+1}_{-1}$ |

Note. The relxillCp model, Equation (2), is used.

We note that the increase of $R_{\text{in}}$ from epochs 1 to 2 in Table 3 is associated with a decrease of the spectral index of the dominant hard component, $\Gamma_{\text{h}}$. This is expected if the cooling of this component is reduced due to fewer disk blackbody photons impinging on that component. On the other hand, we see that the electron temperature decreases, contrary to the above expectation. This shows that the energy balance is more complex, most likely involving changing the optical depth and cooling by synchrotron photons. We note that a similar lack of a correlation between $T_{\text{e}}$ and the spectral hardness is seen in Cyg X-1; see Figures 4 and 6 in Ibragimov et al. (2005). On the other hand, an analogous increase of $R_{\text{in}}$ from epochs 1 to 2 is much weaker in the model using relxillCp; see Table 2. This demonstrates a significant model dependence of the detailed fitting results.

3.2. The NuSTAR, INTEGRAL, and Insight-HXMT Data

We then include the Insight-HXMT data in our spectral models. We fit the LE, ME, and HE data in the 2–10, 10–30, and either the full range of 30–200 keV when using Equation (1) or 30–150 keV with Equation (2). We allow $K$ and $\Delta T$ to be free for the LE and ME data; for HE, we found that $\Delta T$ is compatible with null for epoch 1, and allowing it to be free does not improve the fit. We thus keep it fixed at null and allow only $K$ to be free.

Our results are given in Tables 4 and 5 and Figure 1. We find that the addition of the Insight-HXMT data only moderately changes our results. In particular, the reflecting disk is substantially truncated for all of the fits during both epochs. In all cases, we find $R_{\text{in}} \gtrsim 10 R_{\text{g}}$. However, we see that using the present model and including the Insight-HXMT data results in the reflection components being quite strong for epoch 1 (see Figure 1(a)), while no such issue appeared for the NuSTAR+INTEGRAL data alone fitted in Zdziarski et al. (1996).

Note. The relxillCp model, Equation (2), is used.

where the indices “s” and “h” correspond to the soft and hard thermal Comptonization components, respectively. Note that the low-energy spectral index, $\Gamma$, is constrained to $\geq 1.20$ in relxillCp.

plabs * tbabs(diskbb + relxillCp$_s$ + relxillCp$_h$ + gauss),

where the indices “s” and “h” correspond to the soft and hard thermal Comptonization components, respectively. Note that the low-energy spectral index, $\Gamma$, is constrained to $\geq 1.20$ in relxillCp.

We see that we still obtain fits where the disk is significantly truncated, and the truncation radii for the two reflectors are larger for both epochs (except for $R_{\text{in,s}}$ for the reflection of the soft Comptonization component for epoch 1, which is almost the same as the corresponding one for the relxillkerr model) than the inner truncation radii obtained with the relxillkerr model (of Equation (1)); see Table 2. The differences in the parameters with respect to the relxillkerr models are due to the differences in the models; in particular, relxillCp uses the purely thermal Comptonization model of Zdziarski et al. (1996), rather than the hybrid one of Poutanen & Svensson (1996). Still, the two sets of results are relatively similar.
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Table 4
The Results of Spectral Fitting the NuSTAR+INTEGRAL+Insight-HXMT Data in the 2–650 keV Energy Range

| Component               | Parameter | Epoch 1 | Epoch 2 |
|-------------------------|-----------|---------|---------|
| ISM absorption          | $N_{H}$ [10^{21}] cm^{-2} | 1.4f    |         |
| Joint constraints       | $\eta$ [deg] | 59^{+0}^{-0} | 60^{+1}^{-0} |
|                         | $Z_{\xi}$ [0]  | 2.3^{+0.2}_{-0.1} | 2.1^{+0.2}_{-0.1} |
| Disk                    | $kT_{in}$    | 0.50^{+0.02}_{-0.01} | 0.50^{+0.02}_{-0.01} |
| and a narrow            | $N_{\text{diskbb}}$ [10^{3}] | 3.3^{+0.6}_{-0.6} | 2.6^{+0.4}_{-0.4} |
| 6.40 keV line           | $N_{\text{Fe K}\alpha}$ [10^{3}] | 3.1^{+0.1}_{-0.1} | 2.3^{+0.4}_{-0.4} |
| Thermal                 | $\lambda_{\nu}$ | 0.71^{+0.01}_{-0.01} | 0.61^{+0.01}_{-0.00} |
| Comptonization          | $\Gamma_{\text{in}}$ | 1.62^{+0.01}_{-0.01} | 1.71^{+0.01}_{-0.00} |
| and reflection          | $kT_{e,\text{in}}$ [keV] | 15^{+4.5}_{-4.0} | 12.4^{+3}_{-0.2} |
|                         | $R_{\text{e,th}}$ [R_{g}] | 15^{+1}_{-1} | 15^{+2}_{-2} |
|                         | $R_{\text{th}}$ | 1.40^{+0.05}_{-0.04} | 0.49^{+0.05}_{-0.02} |
|                         | $\log_{10} Z_{\xi}$ | 4.20^{+0.03}_{-0.01} | 3.88^{+0.04}_{-0.04} |
|                         | $N_{\text{H}}$ | 1.62^{+0.01}_{-0.00} | 2.67^{+0.38}_{-0.07} |
| Hybrid                  | $\gamma_{\nu}$ | 1.38^{+0.02}_{-0.02} | 1.03^{+0.03}_{-0.03} |
| Comptonization          | $\Gamma_{e}$ | 1.19^{+0.02}_{-0.02} | 1.27^{+0.02}_{-0.02} |
| and reflection          | $kT_{e,\text{ch}}$ [keV] | 27.5^{+3.3}_{-2.4} | 23.1^{+4.2}_{-5.7} |
|                         | $\gamma_{\text{mm}}$ | 1.26^{+0.16}_{-0.02} | 1.15^{+0.25}_{-0.02} |
|                         | $p$           | 3.66^{+0.18}_{-0.08} | 3.7^{+0.3}_{-0.3} |
|                         | $\Delta R_{[R_{g}]}$ | 17^{+4}_{-2} | 27^{+5}_{-2} |
|                         | $R_{\text{th}}$ | 1.29^{+0.01}_{-0.02} | 0.73^{+0.09}_{-0.02} |
|                         | $\log_{10} Z_{\xi}$ | 6^{+1}_{-1} | 0^{+1}_{-1} |
|                         | $N_{\text{H}}$ | 0.35^{+0.03}_{-0.01} | 0.46^{+0.01}_{-0.01} |
| LE/NuSTAR A             | $\Delta \Gamma$ [10^{-2}] | 0.9^{+0.1}_{-0.1} | 1.0^{+0.1}_{-0.1} |
| ME/NuSTAR A             | $\Delta \Gamma$ [10^{-2}] | 5.0^{+0.2}_{-0.2} | 6.2^{+0.4}_{-0.4} |
| $\chi^{2}_{d}$          | 1684/1192 | 2210/1706 |

Note. The relxillCp model, Equation (1), is used.

We then tested again the effect of allowing the irradiation index, $q$, to be free. While it gave no fit improvement at all in the case of the NuSTAR+INTEGRAL data alone, we find that it now only slightly, by a few, decreases the value of $\chi^{2}$, while the fitted values are $q \gtrsim 2$. Still, those models have similarly large values of the disk truncation radii and show no significant changes in the parameters. We thus have not investigated those models further.

We clearly see apparently spurious high-energy tails in the HE data above $\sim$100 keV. The presence of those upturns has resulted in hardening of the best-fit models, and in consequence, the ISGRI and SPI data are below the model at $\gtrsim$100 keV. Since the calibration of the INTEGRAL detectors is rather well established, with mutual agreement of the spectra from its three high-energy detectors (including the PICsIT), as shown for MAXI J1820+070 in Z21, the actual departure of the high-energy part of the HE spectrum corresponds to the ratio of the HE and INTEGRAL spectra, and it is higher than the departures from the present best fits.

While we also find a low value of $\Delta \Gamma$ for the fitted LE and HE spectra, we find rather high values of the best-fit $\Delta \Gamma \approx 0.05$ and 0.06 for the ME data for epochs 1 and 2, respectively.\footnote{This problem appears to be specific to the Insight-HXMT data for MAXI J1820+070; no such large $\Delta \Gamma$ is found when fitting the Insight-HXMT spectra of either Crab or the BH X-ray binary MAXI J1535–571.}

3.3. Insight-HXMT Data Alone

We then fit the Insight-HXMT data alone. For the sake of simplicity, we fit here only the relxillCp model, Equation (2). Given the results of the joint fitting, we assume $\Delta \Gamma = 0$, $K = 1$ for the HE data. However, we have found that allowing free values of $\Delta \Gamma$ for the LE and ME leads to rather large, and obviously spurious, results. We thus have constrained their absolute values to be within the uncertainty ranges of the corresponding joint fits; see Table 5. Our results are given in Table 6.

We can see that these data alone poorly constrain the inner radius. It is found to be very large for epoch 1 and very small for epoch 2. This is the opposite of the behavior found for the fits with the NuSTAR+INTEGRAL data alone (Table 3) and those including the Insight-HXMT data (Table 5). In those cases, the inner radius for epoch 2 was found to be several times that for epoch 1, with both showing significant disk truncation. This particular Insight-HXMT result is clearly spurious. It appears that the Insight-HXMT data are, unfortunately, not suitable to determine the truncation radii during the evolution of MAXI J1820+070.
Figure 1. Unfolded spectra and data-to-model ratios of epochs (a) 1 and (b) 2, fitted with the model of Equation (1); see Table 4 for the parameters. The error bars show the data from NuSTAR A and B (magenta and cyan, respectively), SPI (blue), ISISRI (red), and Insight-HXMT LE (green), ME (yellow), and HE (black). The spectra are normalized to the NuSTAR A one. The softer (red long dashes) and harder (blue short dashes) Comptonization components are for thermal and hybrid electrons, respectively. The corresponding reflection components are shown by the magenta dotted–dashed and cyan dotted lines, respectively. The disk blackbody and the narrow Fe Kα lines are shown by the black dotted–dashed and yellow dashed lines, respectively. No rebinning has been applied to the plots.

Table 6
The Results of Spectral Fitting the Insight-HXMT Data Only in the 2–150 keV Energy Range

| Component          | Parameter | Epoch 1 | Epoch 2 |
|--------------------|-----------|---------|---------|
| ISM absorption     | N_\text{H} [10^{23}] cm^{-2} | 1.4f    |         |
| Joint constraints  | θ [deg]   | 63^{+4}_{-4} | 59^{+8}_{-0} |
|                    | Z_{\text{Fe}} [\odot] | 1.6^{+0.3}_{-0.3} | 2.0^{+0.4}_{-0.4} |
| Disk               | kT_m [keV] | 0.40^{+0.02}_{-0.02} | 0.45^{+0.05}_{-0.05} |
| and a narrow       | N_{\text{Fe} Kα} [10^{3}] | 4.8^{+3.8}_{-3.3} | 4.4^{+3.3}_{-2.3} |
| 6.40 keV line      | N_{\text{e,s} Kα} [10^{3}] | 2.0^{+0.7}_{-0.9} | 1.7^{+0.8}_{-0.8} |
| Soft               | Γ_s       | 1.73^{+0.03}_{-0.03} | 1.75^{+0.02}_{-0.02} |
| Comptonization     | kT_e [keV] | 13^{+1.3}_{-1.3} | 13^{+1.3}_{-1.3} |
| and reflection      | R_m [R_g] | 230^{+70}_{-75} | 14^{+7.4}_{-6.2} |
|                    | R_s       | 0.5^{+0.2}_{-0.2} | 0.5^{+0.1}_{-0.1} |
|                    | log g_{\text{e,s}} | 4.0^{+0.5}_{-0.6} | 3.6^{+0.3}_{-0.3} |
|                    | N_s [10^{23}] | 7.1^{+0.6}_{-0.5} | 6.9^{+0.5}_{-0.5} |
| Hard               | Γ_h       | 1.27^{+0.05}_{-0.07} | 1.27^{+0.07}_{-0.06} |
| Comptonization     | kT_e [keV] | 32^{+1}_{-1} | 32^{+1}_{-1} |
| and reflection      | R_m [R_g] | 33^{+22}_{-19} | 59^{+44}_{-19} |
|                    | R_s       | 0.5^{+0.4}_{-0.4} | 0.9^{+0.1}_{-0.1} |
|                    | log g_{\text{e,s}} | 0^{+1.8}_{-0.7} | 0^{+1.8}_{-0.7} |
|                    | N_s [10^{23}] | 6.1^{+0.4}_{-0.4} | 6.1^{+0.5}_{-0.4} |
| LE/HE              | ΔΓ [10^{-2}] | −1.4^{+1.6}_{-1.4} | −0.7^{+1.3}_{-0.3} |
| ME/HE              | ΔΓ [10^{-2}] | 4.8^{+5.2}_{-5.0} | 6^{+2}_{-3} |
|                   | χ^2       | 552/370 | 451/370 |

Note. The relxillCp model, Equation (2), is used. The values of R_m obtained here appear spurious, as they are completely different from those obtained using the NuSTAR data; see Tables 2–5.

4. Discussion

We have found good agreement between the overall shapes of the Insight-HXMT data and those of NuSTAR and INTEGRAL. The two main outstanding issues are the slope of the ME data requiring a relatively large correction to bring it into agreement with the NuSTAR data and the presence of apparently spurious high-energy tails in the HE data at E ≥ 10^5 keV. We note, however, that Li et al. (2020) estimated the systematic error of the HE data at 150 keV to be as high as 5%, the inclusion of which would strongly reduce the statistical significance of the tail.

Our major robust result is yet another confirmation of the relatively large inner truncation radii of the reflecting disk in MAXI J1820+070, R_m ≈ 10R_g, for both the NuSTAR data alone and those including Insight-HXMT. On the other hand, the fits of a large set of Insight-HXMT data in Y21 assumed that the disk extends down to the ISCO of a maximally rotating BH, i.e., R_in ≈ 1.2R_g. This disk was irradiated by a corona above it (see Equation (1) in Y21) with a free irradiation index, with a best-fit value of q ≈ 0. Such low values of q are possible only if either the irradiation of the innermost parts of the disk is strongly reduced with respect to the standard coronal dissipation profile (Novikov & Thorne 1973) or those disk parts are strongly fragmented. Alternatively, such values of q may mimic the effect of the zero-stress boundary condition at the
ISCO for a slowly spinning BH, where the peak of the dissipation profile is at \( >10 R_g \). In fact, the parameters \( q \) and \( R_{\text{in}} \) are strongly correlated with each other (Wilkins & Fabian 2012) and often cannot be independently determined.

In the case of the highly accurate NuSTAR data, we have found no fit improvement at all when allowing a free \( q \) and the full compatibility of the models with the standard value of \( q = 3 \). When the Insight-HXMT data are added, we find only slight fit improvements, and \( q \gtrsim 2 \). This difference with respect to the results of Y21 is due to (1) the inner disk assumed at the ISCO in Y21 while estimated from the spectral fits in the present work, and (2) taking into account the spectral complexity of this source in the present work with the presence of two Comptonization regions, the softer one dominating at softer X-rays and a harder one at harder X-rays. Such stratification is also indicated by the presence of hard lags in this source, i.e., harder X-rays delayed with respect to softer ones (De Marco et al. 2021), and by the spectral-timing modeling of Kawamura et al. (2022). The spectral complexity of this source was also found by Buisson et al. (2019), who fitted the NuSTAR spectra with the reflection of two lamposts at different heights. The necessity of spectral complexity in MAXI J1820+070 is discussed in detail by Zdziarski et al. (2021b).

Furthermore, the widths of the Fe K complexes fitted for the Insight-HXMT data alone were found to be significantly different from the fits to the combined NuSTAR and Insight-HXMT data. As found in Section 3.3, the Insight-HXMT data alone did show the reflecting disk at the ISCO for a maximally rotating BH for epoch 2, the opposite of the case of either the NuSTAR or combined data sets; see Sections 3.1 and 3.2. On the other hand, the truncation radius for epoch 1 was found to be very large (Table 6). This comparison indicates that the Insight-HXMT data for MAXI J1820+070 alone are not suitable for detailed X-ray spectroscopy of the Fe K region. Still, the Insight-HXMT data, together with those of NuSTAR, do show moderate truncation radii for both epochs and using two different models.

The inner disk temperatures we have found are \( kT_{\text{in}} \approx 0.4–0.5 \text{keV} \) in all cases, which is significantly higher than the values obtained by fitting the NICER data, which are \( \approx 0.2 \text{keV} \) (Wang et al. 2020). This indicates the presence of a further softening of the apparent Comptonization continuum toward lower energies (see Figure 7 in Zdziarski et al. 2021b), rather the presence of two separate disk blackbody components. Then, our usage of the disk blackbody model should be considered to be only a phenomenological description of inhomogeneous Comptonization/reflection spectra. This is indicated by the apparently complex structure of the accretion flow in the hard state, implied, e.g., by the results of the frequency-resolved spectral fitting of NICER data by Axelsson & Veledina (2021) and Dziefuk et al. (2021); see also Kawamura et al. (2022).

We can also compare our spectral fitting results to some analytical estimates of truncation radius. First, we can use the normalization of the disk blackbody spectral component. This normalization was found at \( N_{\text{diskbb}} \approx 3–4 \times 10^{-2} \) in Tables 4–6. The implied \( R_{\text{in}} \) depends on the color correction, \( \kappa \); see, e.g., Equation (8) in Zdziarski et al. (2021a). This correction has been found to be within \( \kappa \approx 1.3–1.7 \) (Davis et al. 2005). Then, for \( D = 3 \text{kpc}, M = 7 M_\odot \), and \( i = 65^\circ \), we find \( R_{\text{in}}/R_g \) within \( \approx 6–13 \), which is somewhat below our fitted values for joint data. However, we can also estimate the blackbody temperature resulting from irradiation of the disk close to \( R_{\text{in}} \) by the Comptonization emission. The irradiating Comptonization fluxes of the inner soft component for epochs 1 and 2 are \( F_C \approx 3–4 \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \). Absorption of a part \((1 - a)\) of this flux, where \( a \) is the backscattering albedo, results in a quasi-blackbody emission at a temperature above the effective one; see Zdziarski & De Marco (2020). This irradiating temperature is estimated in Equation (9) of Zdziarski et al. (2021a). Typical values of \( a \) for ionized reflecting media were estimated to be within \( a \approx 0.3–0.7 \) (Zdziarski & De Marco 2020). We also neglect here the reduction of the observed Comptonization flux with respect to that irradiating the disk due to scattering in the hot medium, which is a conservative assumption. Then, that formula gives the color temperature due to irradiation alone as \( kT_{\text{in}} \approx 0.6–0.9 \text{keV} \), i.e., more than the fitted inner temperatures. This shows that the assumption that the fitted diskbb corresponds to the actual disk blackbody is unphysical, in agreement with the finding of a lower inner temperature in the NICER data (Wang et al. 2020). Finally, we estimate the inner radius at which irradiation would result in a given inner temperature (Equation (6) in Zdziarski et al. 2021a). This gives relatively large values of \( R_{\text{in}} \gtrsim 50R_g \). Thus, our estimates favor strong truncation.

As we noted above, Y21 interpreted their fits of Insight-HXMT data as showing the presence of an outflowing corona. A strong argument for this was a decrease of the fitted reflection fraction with decreasing spectral hardness, which was, in turn, correlated with the shortening time lags of soft X-rays with respect to hard ones (measured by NICER). This discovery was interpreted as due to the Doppler deboosting of the disk irradiation by a corona whose velocity decreases with height. Note that the values of \( R \ll 1 \) found by them were due to a bug in previous versions of relxill. After the corrections, the fitted values of \( R \) increase by a factor of \( \approx 3 \), but the trend of the decreasing reflection fraction remains present (B. You & A. A. Zdziarski, in preparation).

Still, it is possible that the hard Comptonization component originates in an outflowing corona forming an inner part of the jet (as noticed by Zdziarski et al. 2021b). This was also suggested by Ma et al. (2021) based on the behavior of X-ray quasiperiodic oscillations. Then, bulk-motion Comptonization may provide another spectral component (e.g., Mondal & Chakrabarti 2021). However, including this physical process is beyond the scope of our paper.

Finally, we comment on the relatively low values of the fitted electron temperatures for fits with hybrid Comptonization (Tables 2 and 4). As discussed in Z21c, this may be due to either the onset of pair production by photons scattered by the nonthermal tail (Coppi 1999; Fabian et al. 2017) or the energy balance in the flow emitting synchrotron photons (Poutanen & Urry 2009; Malzac & Belmont 2009). Still, MAXI J1820+070 in the hard state fitted by hybrid Comptonization shows lower values of \( kT_e \) than Cyg X-1 fitted by the same spectral model (McConnell et al. 2002); this may be due to the disk truncation being stronger in Cyg X-1 than in MAXI J1820+070, an effect that may, in turn, be related to a relatively low Eddington ratio in Cyg X-1. Indeed, there is ample evidence for the truncation radius in the hard state decreasing with increasing luminosity; see, e.g., Plant et al. (2015) and Basak & Zdziarski (2016) for such behavior in the BH transient binary GX 339–4. We note,

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\footnote{At the time of preparing the publication of Y21, relxill v1.4.0 was the latest available version, with the bug fixed in v1.4.3; see \url{http://www.sternwarte.uni-erlangen.de/~dauser/research/relxill/}. This version has been used in the present work.}
however, that since both of our chosen data sets correspond to an almost identical bolometric luminosity (and the spectral shape), we cannot study the evolution of the truncation radius with either the luminosity or the accretion rate.

5. Conclusions

Our main results are as follows.

We have performed a thorough analysis of the simultaneous NuSTAR and INTEGRAL observations of MAXI J1820+070 in its hard spectral state. We have extended the original analysis in Z21c and found that the addition of a disk blackbody and unblurred reflection significantly improves the fits. We have tested alternative source geometries to those used in Z21c but found that they provide worse fits. We have also fitted models using the relxill X-ray spectroscopy model and found that it yields similar results to our original models (using relxkerr).

Next, we have included the simultaneous Insight-HXMT data and repeated our fits with relxkerr and relxill. We have found a good mutual agreement between the NuSTAR, INTEGRAL, and Insight-HXMT data, with the fits yielding similar parameters to the previous ones.

In all of the above cases, we have found the reflecting disk to be truncated, with $R_{\text{in}} \gtrsim 10R_g$. We have also tested a possible departure of the irradiation index, $q$, from the canonical value of 3. However, we have found that allowing it to be free does not improve the fits, and the best-fit values remain close to 3. This provides a confirmation for the assumed coronal geometry, with the dissipation rate in the corona following that of the disk. On the other hand, constraints from reemission of the absorbed part of the irradiation flux yield $R_{\text{in}} \gtrsim 10R_g$.

We have fitted the Insight-HXMT data alone. We have found that they cannot constrain the inner disk radius. Our recommendation is that constraints on $R_{\text{in}}$ from other instruments be used.

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References

Arnould, K. A. 1996, in ASP Conf. Ser. 101, XSPEC: The First Ten Years, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Ati, P., Miller-Jones, J. C. A., Bahramian, A., et al. 2020, MNRAS, 493, L81
Axelsson, M., & Veledina, A. 2021, MNRAS, 507, 2744
Bambi, C., Brennaman, L. W., Dauser, T., et al. 2021, SSRv, 217, 65
Basak, R., & Zdziarski, A. A. 2016, MNRAS, 458, 2199
Buisson, D. J. K., Fabian, A. C., Barrett, D., et al. 2019, MNRAS, 490, 1350
Coppi, P. S. 1999, in ASP Conf. Ser. 161, High Energy Processes in Accreting Black Holes, ed. J. Poutanen & R. Svensson (San Francisco, CA: ASP), 375
Courvoisier, T. J. L., Walter, R., Beckmann, V., et al. 2003, A&A, 411, L53
Dauser, T., García, J., Walton, D. J., et al. 2016, A&A, 590, A76
Davis, S. W., Blues, O. M., Hubeny, I., & Turner, N. J. 2005, ApJ, 621, 372
De Marco, B., Zdziarski, A. A., Ponti, G., et al. 2021, A&A, 654, A14
Done, C., Gierliński, M., & Kubota, A. 2007, A&ARv, 15, 1
Dzielak, M. A., De Marco, B., & Zdziarski, A. A. 2021, MNRAS, 506, 2020
Fabian, A. C., Lohfink, A., Belmont, R., Malzac, J., & Coppi, P. 2017, MNRAS, 467, 2866
García, J., & Kallman, T. R. 2010, ApJ, 718, 695
García, J. A., Kallman, T. R., Bautista, M., et al. 2018, in ASP Conf. Ser. 515, Workshop on Astrophysical Opacities, ed. C. Mendoza et al. (San Francisco, CA: ASP), 282
García, J. A., Steiner, J. F., Grinberg, V., et al. 2018, ApJ, 864, 25
Gondreau, K. C., Arzoumanian, Z., Adkins, P. W., et al. 2016, Proc. SPIE, 9905, 99051H
Harrison, F. A., Craig, W. N., Christensen, F. E., et al. 2013, ApJ, 770, 103
Ibragimov, A., Poutanen, J., Gilfanov, M., Zdziarski, A. A., & Shrader, C. R. 2005, MNRAS, 362, 1435
Kara, E., Steiner, J. F., Fabian, A. C., et al. 2019, Nat, 565, 198
Kawamura, T., Axelsson, M., Done, C., & Takahashi, T. 2022, MNRAS, 511, 536
Kawamura, T., Negoro, H., Yoneyama, T., et al. 2018, ATeL, 11399, 1
Lebrun, F., Leray, J. P., Lavocat, P., et al. 2003, A&A, 411, L141
Li, X., Li, X., Tan, Y., et al. 2020, JHEAp, 27, 64
Ma, X., Tao, L., Zhang, S.-N., et al. 2021, NatAs, 5, 94
Malzac, J., & Belmont, R. 2009, MNRAS, 392, 570
Marino, A., Barnier, S., Petrucci, P. O., et al. 2021, A&A, 656, A63
McConnell, M. L., Zdziarski, A. A., Bennett, K., et al. 2002, ApJ, 572, 984
Mitsuda, K., Inoue, H., Koyama, K., et al. 1984, PASJ, 36, 741
Mondal, S., & Chakrabarti, S. K. 2021, ApJ, 920, 41
Niedźwiecki, A., Szaniecki, M., & Zdziarski, A. A. 2019, MNRAS, 485, 2942
Novikov, I. D., & Thorne, K. S. 1973, in Black Holes (Les Astres Occlus), ed. C. Dewitt & B. S. Dewitt (New York: Gordon & Breach), 343
Plant, D. S., Fender, R. P., Ponti, G., Muñoz-Darias, T., & Coriat, M. 2015, A&A, 573, A120
Poutanen, J., & Svensson, R. 1996, ApJ, 470, 249
Poutanen, J., & Vurm, I. 2000, ApJL, 590, L97
Roques, J.-P., & Jourdain, E. 2019, ApJ, 870, 92
Roques, J. P., Schanne, S., von Kienlin, A., et al. 2003, A&A, 411, L91
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Torres, M. A. P., Casares, J., Jiménez-Ibarra, F., et al. 2020, ApJL, 893, L37
Tucker, M. A., Shappee, B. J., Holoien, T. W. S., et al. 2018, ApJL, 867, L9
Wang, J., Mastroserio, G., Kara, E., et al. 2021, ApJL, 910, L3
Wang, Y., Ji, L., Zhang, S. N., et al. 2020, ApJ, 896, 33
Wilkins, D. R., & Fabian, A. C. 2012, MNRAS, 424, 1284
Wood, C. M., Miller-Jones, J. C. A., Homan, J., et al. 2021, MNRAS, 505, 3393
You, B., Tu, Y., Li, C., et al. 2021, NatCo, 12, 1025
Zdziarski, A. A., & De Marco, B. 2020, ApJL, 896, L36
Zdziarski, A. A., De Marco, B., Szaniecki, M., Niedźwiecki, A., & Markowitz, A. 2021a, ApJL, 906, 69
Zdziarski, A. A., Dzielak, M. A., De Marco, B., Szaniecki, M., & Niedźwiecki, A. 2021b, ApJL, 909, L9
Zdziarski, A. A., Johnson, W. N., & Magdziarz, P. 1996, MNRAS, 282, 193
Zdziarski, A. A., Jourdain, E., Lubinski, P., et al. 2021c, ApJL, 914, L5
Zhang, S., Lu, F. J., Zhang, S. N., & Li, T. P. 2014, Proc. SPIE, 9144, 91442I