Suspended and Restored Activities of a Nearby Supermassive Black Hole

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Abstract

The discovery of spectral type transition of active galactic nuclei (AGNs), the so-called “changing-look” (CL) phenomenon, challenges the widely accepted AGN paradigm, not only in the orientation-based unified model, but also in the standard disk model. In past decades, only a couple of nearby repeat changing-look active galactic nuclei (CL-AGNs) have been identified. Here we report spectroscopic observations of UGC 3223 over the course of 18 yr, from 2001 onwards. Combining the spectrum taken in 1987 by Stirpe, we have witnessed its type transitions from 1.5 → 2.0 → 1.8 over 32 yr, and captured a long-lived (at least 10 yr) thorough “turn-off” state with a spectrum typical of a Seyfert 2 galaxy. The long-term thorough turn-off state probably suggests a once-dormant and an awakening central engine in UGC 3223. We argue that the (dis)appearance of the broad Balmer emission lines can be explained by the disk–wind broad-line region model given the evolution of the calculated Eddington ratio of accretion of the supermassive black hole.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Emission line galaxies (459)

Supporting material: data behind figure

1. Introduction

Multi-epoch spectroscopy recently enables us to reveal a batch of the so-called “changing-look” active galactic nuclei (CL-AGNs) that show a spectral type transition between type I, intermediate type, and type II within a timescale of an order of years or decades. So far, the CL phenomenon has been identified by spectroscopy in only ~80 AGNs, including both “turn-on” and “turn-off” transitions (e.g., MacLeod et al. 2010, 2016; Shapovalova et al. 2010; Shappee et al. 2014; LaMassa et al. 2015; McElroy et al. 2016; Ruan et al. 2016; Runnoe et al. 2016; Parker et al. 2016; Gezari et al. 2017; Stern et al. 2018; Yang et al. 2018; Wang et al. 2018; 2019b; Frederick et al. 2019; Trakhtenbrot et al. 2019; Yan et al. 2019). Based on the Catalina Real-time Transient Survey, Graham et al. (2020) recently identified 111 “changing-state” quasars according to their optical and mid-infrared photometric behavior and spectroscopic change.

The observed CL phenomenon challenges the traditional understanding of AGNs in two points. At first, there is competing evidence in both middle infrared and polarization supporting that the optical CL phenomenon is due to a variation of the accretion rate of a supermassive black hole (SMBH); e.g., Gezari et al. 2017; Sheng et al. 2017; Rumbaugh et al. 2018; Stern et al. 2018; Wang et al. 2018, 2019b; Yang et al. 2018; Hutsemekers et al. 2019; Macleod et al. 2019; Aï et al. 2020), rather than the orientation effect (e.g., Antonucci 1993). Second, there is a viscosity crisis, in which the expected viscous timescale of optical emission coming from the outer accretion is larger than the timescale of the observed CL phenomenon by an order of magnitude (e.g., Lawrence 2018 and references therein). This crisis could be theoretically resolved by introducing a local disk thermal instability (e.g., Husemann et al. 2016; Jiang et al. 2016) or a magnetic field (e.g., Ross et al. 2018; Stern et al. 2018; Dexter & Begelman 2019).

Even though most of the CL-AGNs are identified in the case of two-epoch spectroscopy, repeat type transitions have been identified in only a few nearby Seyfert galaxies and quasars: Mrk 590, Mrk 1018, NGC 1566, NGC 4151, NGC 7603, Fairall 9, and 3C 390.3 (Marin et al. 2019; Parker et al. 2019). Among these objects, only Mrk 590 shows a thorough disappearance of its broad-line region (BLR) emission (Denney et al. 2014). We here report a discovery of a new nearby CL-AGN, UGC 3223, with repeat type transition and a prolonged thorough turn-off of the activity of the SMBH.

The paper is organized as follows. Section 2 describes our repeat spectroscopic observations and data reductions. The spectral analysis is presented in Section 3. Section 4 presents the results and discussion. A ΛCDM cosmology with parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ is adopted throughout the paper.

2. Observations and Data Reduction

UGC 3223 (=MCG +01-13-012, R.A. = 04h59m09.4, decl. = +04°58′30″, J2000) is a local AGN at a redshift of $z = 0.015621$. It was classified as a Seyfert 1.5 galaxy in the catalog of quasars and active nuclei (12th edition; Veron-Cetty & Veron 2006) according to the spectroscopy taken in 1987 (Stirpe 1990).

2.1. Spectroscopic Observations

The long-slit spectra of UGC 3223 have been taken by us using the 2.16 m telescope (Fan et al. 2016) at the Xinglong observatory of National Astronomical Observatories, Chinese Academy of Sciences (NAOC) in four epochs from 2001 to 2019 (see column (1) in Table 1). The observations were carried out with the Optomechanics Research Inc. spectograph equipped with a back-illuminated SPEC 1340 × 400 CCD as the detector. A grating of...
### Table 1
Spectral Measurements and Analysis

| Date         | F(Hβ)  | F([O III] λ5007) (10^{-15} erg s^{-1} cm^{-2}) | F(Hα) | F(Hβ) (km s^{-1}) | F(Hα) (10^{-15} erg s^{-1} cm^{-2}) | FWHM(Hβ) (km s^{-1}) | FWHM(Hα) (km s^{-1}) | M_{BH}/M_{⊙} | L/L_{Edd} |
|--------------|--------|-----------------------------------------------|-------|-------------------|-------------------------------------|----------------------|----------------------|---------------|-----------|
| 1987 Jan 14^a | 12.0   | 47.9                                          | 33.0  | 85.1              | 4740                                | 275.4                | 3980                  | 2.1 \times 10^7 | 0.014     |
| 2001 Nov 16  | 6.5 ± 1.6 | 46.3 ± 3.5                                    | 56.5 ± 6.4 | ...             | ...                                | ...                  | ...                   | ...           | ...       |
| 2003 Oct 25  | 9.6 ± 1.2 | 51.1 ± 2.4                                    | 47.1 ± 4.4 | ...             | ...                                | ...                  | ...                   | ...           | ...       |
| 2010 Nov 9   | 9.8 ± 2.0 | 48.3 ± 5.5                                    | 56.1 ± 4.8 | ...             | ...                                | ...                  | ...                   | ...           | ...       |
| 2019 Sep 6   | 6.7 ± 1.6 | 30.9 ± 2.5                                    | 30.5 ± 3.2 | 17.6 ± 1.6       | 7600 ± 2600                         | 167.5 ± 5.0          | 7800 ± 200             | (9.8 ± 2.8) \times 10^7 | 0.004 ± 0.001 |

Note.

^a The data are quoted from Stirpe (1990).
300 grooves mm$^{-1}$ and a slit of 2″ oriented in the south–north direction were used in the observations. This setup finally leads to a spectral resolution of $\sim 9$ Å as measured from the sky emission lines and comparison arcs. The blazed wavelength was fixed at 6000 Å in all the observation runs, which provides a wavelength coverage from 3400 to 8600 Å in the observer frame. In each of the runs, the object was observed twice in succession. The exposure time of each frame ranges from 1500 to 3600 s. The wavelength and flux calibrations were carried out by the helium–neon–argon comparison arc taken between the two successive frames, i.e., at the position nearly identical to that of the object, and by the Kitt Peak National Observatory (KPNO) standard stars (Massey et al. 1988), respectively.

2.2. Data Reduction

We reduced the two-dimensional spectra by the standard procedures through the IRAF package. At first, the bias subtraction and flat-field correction were applied to each observed frame. In each observation run, the two frames were combined prior to the extraction to enhance the signal-to-noise ratio and to eliminate the contamination of cosmic rays easily. Each extracted one-dimensional spectrum was then calibrated in wavelength and flux by the corresponding comparison arc and standard. The two telluric features A and B around $\lambda 7600$ and $\lambda 6800$ due to the O$_2$ molecules were removed from each extracted spectrum by the corresponding standard. The Galactic extinction was then corrected for each extracted spectrum by the extinction magnitude of $A_V = 0.229$ (Schlafly & Finkbeiner 2011) taken from the NASA/IAAC Extragalactic Database (NED), assuming the $R_V = 3.1$ extinction law of our Galaxy (Cardelli et al. 1989). The spectra were then transformed to the rest frame according to its redshift. The rest-frame spectra taken at the four different epochs are displayed in Figure 1 (the middle curve in each panel).

3. Spectral Analysis

One can see clearly from the figure a lack of broad H$\alpha$ emission line in the three Xinglong spectra taken in 2001, 2003, and 2011, which is different from the spectrum shown in Stirpe (1990). It is interesting that the broad H$\alpha$ emission and a weak H$\beta$ broad emission return back in the 2019 spectrum.
spectral analysis is performed as follows to quantify the type of transition in UGC 3223.

3.1. Removing the Starlight Component

The starlight component of each of the four spectra is at first modeled by a linear combination of the first seven eigenspectra through a $\chi^2$ minimization. The eigenspectra are built from the standard single stellar population spectral library developed by Bruzual & Charlot (2003). An intrinsic extinction due to the host galaxy described by the Galactic extinction curve with $R_V = 3.1$ is also involved in our fitting. The minimization is carried out over the rest-frame wavelength range from 3700 to 8000 Å, except for the regions with strong emission lines, e.g., Balmer lines (both narrow and potential broad components), $[\text{O III}]\lambda\lambda4959, 5007$, $[\text{N II}]\lambda\lambda6548, 6583$, $[\text{S II}]\lambda\lambda6716, 6731$, $[\text{O II}]\lambda3727$, $[\text{O III}]\lambda4363$, and $[\text{O I}]\lambda6300$. Because the absorption features in the observed spectra are dominated by the instrumental profile, the starlight templates are convolved with a fixed Gaussian profile before the minimization. The starlight component, along with the starlight-subtracted spectrum, are shown in Figure 1.

3.2. Line Profile Modeling

In each starlight-subtracted spectrum, we model the emission line profiles by a linear combination of a set of Gaussian functions for the $\text{H}/\beta$ (left panels) and $\text{H}/\alpha$ (right panels) regions. Regions with strong emission lines, e.g., Balmer lines (both narrow and potential broad components), $[\text{O III}]\lambda\lambda4959, 5007$, $[\text{N II}]\lambda\lambda6548, 6583$, $[\text{S II}]\lambda\lambda6716, 6731$, $[\text{O II}]\lambda3727$, $[\text{O III}]\lambda4363$, and $[\text{O I}]\lambda6300$. The line profile modelings, along with the results quoted from Stirpe (1990) for the 1987 spectrum, are listed in Table 1.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** An illustration of line profile modelings by a linear combination of a set of Gaussian functions for the $\text{H}/\beta$ (left panels) and $\text{H}/\alpha$ (right panels) regions. In each panel, the modeled continuum has already been removed from the original observed spectrum. The observed and modeled line profiles are plotted by black and red solid lines, respectively. Each Gaussian function is shown by a dashed line. The subpanel underneath the line spectrum presents the residuals between the observed and modeled profiles.
The uncertainties cannot be determined for the 1987 spectrum because of the lack of errors of the measured parameters in Stirpe (1990).

### 3.3. Black Hole Mass and Eddington Ratio

We then estimate the SMBH virial mass \( M_{\text{BH}} \) and Eddington ratio \( L_{\text{bol}}/L_{\text{Edd}} \) (where \( L_{\text{Edd}} = 1.26 \times 10^{38} M_{\text{BH}}/M_\odot \) erg s\(^{-1}\) is the Eddington luminosity) of UGC 3223 from the modeled broad \( \text{H}\alpha \) emission lines, according to several well-established calibrated relationships (e.g., Kaspi et al. 2000, 2005; Marziani & Sulentic 2012; Du et al. 2014, 2015; Peterson 2014).

The calibration given by Greene & Ho (2007)

\[
M_{\text{BH}} = 3.0 \times 10^6 \left( \frac{L_{\text{bol}}}{10^{42} \text{ erg s}^{-1}} \right)^{0.45} \left( \frac{\text{FWHM}(\text{H}\alpha)}{1000 \text{ km s}^{-1}} \right)^{2.06} M_\odot
\]

is used to estimate \( M_{\text{BH}} \). To obtain an estimation of \( L_{\text{bol}}/L_{\text{Edd}} \), we derive the bolometric luminosity \( L_{\text{bol}} \) from the standard bolometric correction \( L_{\text{bol}} = 9 \lambda L_{\lambda}(5100 \text{ Å}) \) (e.g., Kaspi et al. 2000), where \( L_{\lambda}(5100 \text{ Å}) \) is the AGN’s specific continuum luminosity at 5100 Å. This specific luminosity can be inferred from the \( \text{H}\alpha \) broad-line luminosity through the calibration (Greene & Ho 2005)

\[
\lambda L_{\lambda}(5100 \text{ Å}) = 2.4 \times 10^{43} \left( \frac{L_{\text{H}\alpha}}{10^{42} \text{ erg s}^{-1}} \right)^{0.86} .
\]

The estimated \( M_{\text{BH}} \) and \( L_{\text{bol}}/L_{\text{Edd}} \) are tabulated in columns (9) and (10) in Table 1, along with the uncertainties, respectively, after taking into account both the proper error propagation and the uncertainties of the used calibrations.\(^6\) In the estimation of \( L_{\text{H}\alpha} \), the intrinsic extinction has been corrected from the narrow-line ratio \( \text{H}\alpha/\text{H}\beta \), assuming the Balmer decrement of standard case B recombination and a Galactic extinction curve with \( R_V = 3.1 \).

An extremely low \( L_{\text{bol}}/L_{\text{Edd}} = 0.004 \pm 0.001 \) is finally found from the 2019 spectrum.

### 4. Results and Discussion

The local AGN UGC 3223, which was originally classified as a Seyfert 1.5 galaxy, has been spectroscopically observed by us in four different epochs in the past 19 yr. Our observations and spectral analysis indicate that the object changes to a Seyfert 2 galaxy without broad Balmer emission lines in the spectra taken in 2001, 2003, and 2011. A re-appearance of the broad \( \text{H}\alpha \) emission line (and also of a weak \( \text{H}\beta \) broad emission) is found in our 2019 spectrum, although the line width of the broad \( \text{H}\alpha \) in 2019 is about twice of the value obtained from the 1987 spectrum (Stirpe 1990).

We argue that the lack of a broad Balmer component in the 2001, 2003, and 2010 spectra is not due to their low spectral resolution. First, the Balmer lines in the three spectra have measured line widths close to those of the forbidden narrow emission lines. Second, the average narrow-line ratio of \( F(\text{H}\alpha + \text{N} \equiv \lambda \lambda 6548, 6583)/F(\text{S} \equiv \lambda \lambda 6716, 6731) \) is 4.21 for the three spectra, which is highly consistent with the value of 4.19 of the 2019 spectrum. This consistency indicates that there is unlikely a potential broad component in the modeled line profiles of the three spectra.

Figure 3 shows the multiwavelength light curves of UGC 3223. Within the epochs of the last two spectra, its mid-infrared (MIR) brightness detected by the Wide-field Infrared Survey Explorer (WISE and NEOWISE-R; Wright et al. 2010; Mainzer et al. 2014) increases gradually when the object changes from a type-II AGN to a type-1.8 AGN, which supports the scenario that the type transition is likely due to the enhancement of the accretion rate rather than the obscuring effect (e.g., Sheng et al. 2017; Stern et al. 2018; Wang et al. 2019b).

Even though a breath of the BLR has been previously discovered in a few local AGNs by long-term monitoring, a thorough disappearance of the BLR emission is still rare. To our best knowledge, Mrk 590 was the first, and maybe the only repeat CL-AGN that shows an “on-off-on” transition sequence with a thorough “turn-off.” The spectrum taken in 2014...
indicates that Mrk 590 finally changed to a true Seyfert 2 galaxy from a typical type-I AGN (Denney et al. 2014). After a period of a few years, the object awakes and turns back a type-I AGN (Mathur et al. 2018; Raimundo et al. 2019). Similar to Mrk 590 and UGC 3223, Mrk 1018 changes from type 1.9 to type 1.0 in the spectrum taken in the 1980s (Cohen et al. 1986), and changes back type 1.9 in the 2016 spectrum (Husemann et al. 2016; McElroy et al. 2016).

Figure 4 compares UGC 3223 to the whole AGN population and to a compilation of known CL-AGNs (Wang et al. 2019b) by marking it on the distributions of $L_{\text{bol}}/M_{\text{BH}}$ (left panel) and $L_{\text{bol}}/L_{\text{Edd}}$ (right panel). UGC 3223 marginally stands out of the known CL-AGNs due to the lowest $L/L_{\text{Edd}} \approx 0.004$. SDSS J233602.98+001728.7 at $z = 0.243$ is located adjacent to UGC 3223 in both distributions. It is interesting that SDSS J233602.98+001728.7 shows similarity to UGC 3223 in the type of transition from type 1.5 to type 2 (Ruan et al. 2016), although its repeat transition has not yet been discovered.

Two scenarios can potentially account for the discovered repeat transition with a thorough turn-off exhibition. On the one hand, the disappearance and re-appearance of the BLR can be understood in the context of the previously proposed disk–wind BLR models, because the $L_{\text{bol}}/L_{\text{Edd}}$ of UGC 3223 is closest to the critical value predicted by the disk–wind models. A critical value of $L_{\text{bol}}/L_{\text{Edd}} \approx 2 - 3 \times 10^{-3}$ is in fact proposed byNicastro (2000) for a black hole mass within a range of $10^{4.1 - 4.5} M_\odot$. This critical value is resulted from a critical radius of the accretion disk where the power deposited into the vertical outflow is the maximum. In the model proposed in Elitzur & Ho (2009), an observable BLR cannot be sustained below a certain luminosity, $L \approx 5 \times 10^{39} (M_{\text{BH}}/10^7 M_\odot)^{2/3}$ erg s$^{-1}$, because the mass outflow rate scales with $L$ as $L^{1/4}$ (Elitzur & Shlosman 2006). A much lower critical value of $L_{\text{bol}}/L_{\text{Edd}} \sim 10^{-6}$ is therefore predicted for a transition between the disappearance and appearance of the BLR when the fiducial values of a set of parameters of the disk are adopted. In the case of UGC 3223, the

5. Conclusion

The nearby Seyfert galaxy UGC 3223 is identified as a new repeat CL-AGN by our multispectroscopy carried out from 2001 to 2019. The object shows a type transition of $1.5 \rightarrow 2 \rightarrow 1.8$ within a period of about 30 yr, and a thorough turn-off state for at least 10 yr. We argue that the type transition of UGC 3223 not only could be explained by the disk–wind BLR model, but also suggests a once-dormant and reactive central engine. We finally state that our proposed space-based ultraviolet patrol mission (Wang et al. 2019a) is potentially an effective way for selecting CL-AGN candidates and studying the nature of these objects.

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Facility: NAOC 2.16 m telescope.

Software: IRAF (Tody 1986, 1992).

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References

Ai, Y., Dou, L., Yang, C., et al. 2020, ApJL, 890, L29
Antonucci, R. R. J. 1993, ARA&A, 31, 473
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cohen, R. D., Rudy, R. J., Puetter, R. C., Ake, T. B., & Foltz, C. B. 1986, ApJ, 311, 135
Denney, K. D., De Rosa, G., Croxall, K., et al. 2014, ApJ, 796, 134
Dexter, J., & Begelman, M. C. 2019, MNRAS, 483, L17
Du, P., Hu, C., Lu, K. X., et al. 2015, ApJ, 806, 22
Du, P., Wang, J. M., Hu, C., et al. 2014, MNRAS, 438, 2828
Elitzur, M., & Shlosman, I. 2006, ApJL, 648, 101
Fan, Z., Wang, H. J., Jiang, X. J., et al. 2016, PASP, 128, 115005
Frederick, S., Gezari, S., Graham, M. J., et al. 2019, ApJ, 883, 31
Gezari, S., Hung, T., Cenko, S. B., et al. 2017, ApJ, 835, 144
Graham, M. J., Ross, N. P., Stern, D., et al. 2020, MNRAS, 491, 4925
Greene, J. E., & Ho, L. C. 2005, ApJ, 630, 122
Greene, J. E., & Ho, L. C. 2007, ApJ, 670, 92
Husemann, B., Urrutia, T., Tremblay, G. R., et al. 2016, A&A, 593, L9
Hutsemekers, D., Agis Gonzalez, B., Marin, F., et al. 2019, A&A, 625, A54
Jiang, Y. F., Davis, S. W., & Stone, J. M. 2016, ApJ, 827, 10
Kaspi, S., Maoz, D., Netzer, H., et al. 2005, ApJ, 629, 61
Kaspi, S., Smith, P. S., Netzer, H., et al. 2000, ApJ, 533, 631
Kris, G. 1994, in ASP Conf. Ser. 61, Astronomical Data Analysis Software and Systems III, ed. D. R. Crabbree, R. J. Hanisch, & J. Barnes (San Fransisco, CA: ASP), 437
LaMassa, S. M., Cales, S., Moran, E. C., et al. 2015, ApJ, 800, 144
Lawrence, A. 2018, NatAs, 2, 102
MacLeod, C. L., Green, P. J., Anderson, S. F., et al. 2019, ApJ, 874, 8
MacLeod, C. L., Ivezic, Z., Kochanek, C. S., et al. 2010, ApJ, 721, 1014
MacLeod, C. L., Ross, N. P., Lawrence, A., et al. 2016, MNRAS, 457, 389
Mainzer, A., Bauer, J., Cutri, R. M., et al. 2014, ApJ, 792, 30
Marin, F., Hutsemekers, D., & Agis Gonzalez, B. 2019, in Proc. Annual Meeting of the French Society of Astronomy and Astrophysics, ed. P. Di Matteo, O. Crevyey, A. Crida et al. (Paris: SF2A), 509
Marziani, P., & Sulentic, J. W. 2012, NewAR, 56, 49
Massey, P., Strobel, K., Barnes, J. V., et al. 1988, ApJ, 328, 315
Mathur, S., Denney, K. D., Gupta, A., et al. 2018, ApJ, 886, 123
McElroy, R. E., Husemann, B., Croom, S. M., et al. 2016, A&A, 593, L8
Nicastro, F. 2000, ApJL, 530, 65
Petersson, B. M. 2014, SSRv, 183, 253
Parker, M. L., Komossa, S., Kollatschny, W., et al. 2016, MNRAS, 461, 1927
Parker, M. L., Schartel, N., Grupe, D., et al. 2019, MNRAS, 483, L88
Raimundo, S. I., Vestergaard, M., Koay, J. Y., et al. 2019, MNRAS, 486, 123
Ross, N. P., Ford, K. E. S., Graham, M., et al. 2018, MNRAS, 480, 4468
Ruan, J. J., Anderson, S. F., Cales, S. L., et al. 2016, ApJ, 826, 188
Runnbaugh, N., Shen, Y., Morganson, E., et al. 2018, ApJ, 854, 160
Runnroe, J. C., Cales, S., Ruan, J. J., et al. 2016, MNRAS, 455, 1691
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Shapovalova, A. I., Popovic, L. C., Burenkov, A. N., et al. 2010, A&A, 509, 106
Shappee, B. J., Prieto, J. L., Grupe, D., et al. 2014, ApJ, 788, 48
Sheng, Z., Wang, T., Jiang, N., et al. 2017, ApJL, 846, 7
Stern, D., McKernan, B., Graham, M. J., et al. 2018, ApJ, 864, 27
Sturpe, G. M. 1990, A&AS, 85, 1049
Tody, D. 1986, Proc. SPIE, 627, 733
Tody, D. 1992, in ASP Conf. Ser. 52, Astronomical Data Analysis Software and Systems II, ed. R. J. Hanisch, R. J. V. Brissenden, & J. Barnes (San Fransisco, CA: ASP), 173
Trakhtenbrot, B., Arcavi, I., MacLeod, C. L., et al. 2019, ApJ, 883, 94
Veron-Cetty, M.-P., & Veron, P. 2006, A&A, 455, 773
Wang, J., Liang, E. W., & Wei, J. Y. 2019a, PASP, 131, 095001
Wang, J., Xu, D. W., Wang, Y., et al. 2019b, ApJ, 887, 15
Wang, J., Xu, D. W., & Wei, J. Y. 2018, ApJ, 858, 49
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Yan, L., Wang, T. G., Jiang, N., et al. 2019, ApJ, 874, 44
Yang, Q., Wu, X. B., Fan, X. H., et al. 2018, ApJ, 862, 109