Multiwavelength Observations of Sgr A*. I. 2019 July 18

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Abstract

We present and analyze ALMA submillimeter observations from a multiwavelength campaign of Sgr A* during 2019 July 18. In addition to the submillimeter, we utilize concurrent mid-infrared (mid-IR; Spitzer) and X-ray (Chandra) observations. The submillimeter emission lags less than \(\delta t \approx 30\) minutes behind the mid-IR data. However, the entire submillimeter flare was not observed, raising the possibility that the time delay is a consequence of incomplete sampling of the light curve. The decay of the submillimeter emission is not consistent with synchrotron cooling. Therefore, we analyze these data adopting an adiabatically expanding synchrotron source that is initially optically thick or thin in the submillimeter, yielding time-delayed or synchronous flaring with the IR, respectively. The time-delayed model is consistent with a plasma blob of radius 0.8 \(R_S\) (Schwarzschild radius), electron power-law index \(p = 3.5\ \frac{N(E) \propto E^{-p}}{}\), equipartition magnetic field of \(B_{\text{eq}} \approx 90\) Gauss, and expansion velocity \(v_{\text{exp}} \approx 0.004c\). The simultaneous emission is fit by a plasma blob of radius 2 \(R_S\), \(p = 2.5\), \(B_{\text{eq}} \approx 27\) Gauss, and \(v_{\text{exp}} \approx 0.014c\). Since the submillimeter time delay is not completely unambiguous, we cannot definitively conclude which model better represents the data. This observation presents the best evidence for a unified flaring mechanism between submillimeter and X-ray wavelengths and places significant constraints on the source size and magnetic field strength. We show that concurrent observations at lower frequencies would be able to determine if the flaring emission is initially optically thick or thin in the submillimeter.

Unified Astronomy Thesaurus concepts: Galactic center (565); Active galactic nuclei (16); Supermassive black holes (1663)

1. Introduction

Sagittarius A* (Sgr A*) is the 4.297 \(\times\) 10^6 \(M_\odot\) supermassive black hole located at a distance of 8.27 kpc (Gravity Collaboration et al. 2019) in the center of the Milky Way. It is known to be a variable source at radio through X-ray wavelengths (e.g., Yusef-Zadeh et al. 2006; Dodds-Eden et al. 2009; Dexter et al. 2014; Hora et al. 2014) and is a prime target to understand how gas is captured, accreted, and/or ejected from low-luminosity supermassive black holes.

At infrared (IR) and X-ray wavelengths, the emission from Sgr A* is optically thin synchrotron radiation (e.g., Eckart et al. 2004, 2006, 2012; Ponti et al. 2017; Witzel et al. 2021). At submillimeter and radio wavelengths, the variable emission’s timescale is much shorter than that of the synchrotron cooling time. Yusef-Zadeh et al. (2006) used an adiabatically expanding synchrotron plasma (van der Laan 1966) to describe the emission observed in this frequency range with much success. Since then, there has been a formidable effort to connect the radio/submillimeter and IR/X-ray regimes with a model that can explain the variable emission across the electromagnetic spectrum. Multiwavelength campaigns (e.g., Yusef-Zadeh et al. 2008; Eckart et al. 2009; Mossoux et al. 2016; Ponti et al. 2017; Subroweit et al. 2020; Witzel et al. 2021) are critical to test this picture. Nonoverlapping observations (due to the rise/set times at different observatories) and time-delayed emission at radio frequencies make this a difficult task. This has been somewhat alleviated by space-based IR instruments, like the Spitzer Space Telescope, in concert with submillimeter observations, like ALMA (e.g., Witzel et al. 2021). Submillimeter observations are key as they lay near the “submillimeter bump” (Zylka et al. 1992, 1995), where Sgr A* is brightest. This bump begins in the millimeter and decays at wavelengths near the far-IR, where the emission becomes increasingly optically thin, and optical depth effects are unimportant (Marrone 2006).

Abuter et al. (2021) recently published an analysis from a multiwavelength campaign on 2019 July 18 using IR and X-ray data. Here, we present simultaneous ALMA observations, which show a time delay relative to the mid-IR data, suggesting an optically thick and dynamically evolving source.

2. Observations and Data Reduction

The campaign included data from the Very Large Array (VLA) and Giant Metrewave Radio Telescope (GMRT) on 2019 July 18; however, these light curves are not useful for this date. The VLA data at the Q band could not be calibrated by the VLA pipeline owing to bad weather and long cycle times. Extended structures in the GMRT data dominated Sgr A*, and identifying the intrinsic variability of Sgr A* is difficult. A more detailed account of these data will be given in J. Michail et al. (2021, in preparation).

2.1. Submillimeter: ALMA

The ALMA data used were taken as part of a Cycle 6 Atacama Compact Array (ACA) observatory filler program (project code 2018.A.00050.T), which observed the Galactic Center in Band 7 on 2019 July 18 for about 7 hr. The data set was calibrated and imaged by the ALMA pipeline (Pipeline-CASA54-P1-B, r42254, CASA v5.4.0–70; McMullin et al. 2007). The calibrated measurement set was obtained by restoring the calibration from the ALMA archive using
The data consist of four spectral windows of 2 GHz bandwidth and a spectral resolution of 1.953 MHz, with one spectral window centered on the CO transition at 346 GHz and three continuum spectral windows. J1337–1257 and J1924–2914 were used as bandpass and amplitude calibrators. J1700–2610 (J1700) and J1717–3342 were used as phase calibrators throughout the observation. J1733–3722 (J1733) was the phase calibration during the last execution block. There were calibration issues in the gain amplitudes between the first three execution blocks; this was readily apparent in the light curve of J1700–2610, which showed that the flux varied by approximately 10%. To fix these offsets, we calculate average scale factors for the second and third execution blocks relative to the first using J1700–2610. These amplitude scale factors are applied to Sgr A* and J1700–2610. We chose the first execution block as our standard as its flux was most similar to J1700–2610’s on the night of 2019 July 19. We do not complete the same scaling procedure for the last execution block as the phase calibrator is J1733–3722. The observation was imported into AIPS for phase self-calibration. Then, DFTPL was used to extract the light curves from Sgr A* at a 60 s binning time. The light curve for each spectral window is calculated independently using baselines greater than 20 kλ. The ALMA light curves are shown in Figure 1 (left).

2.2. Mid-infrared: Spitzer

We obtained the binned Spitzer light curves of Sgr A* for this day of observation (Spitzer Sgr A* Collaboration 2021, private communication), which were originally published in Abuter et al. (2021). Details of these observations are given in the aforementioned paper. Briefly, the IRAC instrument (Fazio et al. 2004) on the Spitzer Space Telescope (Werner et al. 2004) observed Sgr A* as part of Spitzer program 14026 (Fazio et al. 2018) at 4.5 μm. The total on-source time for this observation was approximately 16 hr. Hora et al. (2014) and Witzel et al. (2018) give further details on the observing mode and data reduction. The light-curve time stamps were originally in the barycentric UT system. We converted these to UTC using an online tool (Eastman et al. 2010). The fluxes shown in Figure 1 (center) are relative to a period where Sgr A* is semiquiescent and are not absolute (Hora et al. 2014). These data are dereddened using the extinction value in Fritz et al. (2011) for the Band 2 IRAC instrument ($A_{4.5\mu m} = 1.06$ mag). This yields a correction factor $f_{4.5\mu m} = 2.5121.06 = 2.65$. The dereddened Spitzer light curve for 2019 July 18 is shown in Figure 1 (center).

2.3. X-Ray: Chandra

Three days of simultaneous observations of Sgr A* were completed with the Chandra X-ray Observatory. The corresponding observation ID for 2019 July 18 is 22230 (PI: Fazio) and was first published in Abuter et al. (2021). This observation lasted 52 ks using Chandra’s FAINT mode. Sgr A* was centered on the ACIS-S3 chip using the 1/8 subarray mode to reduce the possibility of pileup events from bright Galactic Center sources. The data are reprocessed with CHANDRA_R-EPRO using CIAO v4.13 and CALDB v4.9.4. The WCS solutions are corrected using the wcs_match and wcs_update scripts utilizing three X-ray bright sources near Sgr A* from the Chandra Source Catalogue (CSC; Evans et al. 2010) in DS9. One of these three sources is the nearby magnetar (SGR J1745–2900) that was readily apparent. The norm of the WCS correction is about 2 pixels (1″).

To obtain background-subtracted light curves of Sgr A*, we follow Capellupo et al. (2017, and references therein). A 1.″25 radius aperture is centered at the J2000.0 radio location of Sgr A* (17°45′00″, −29°00′28″) to minimize contamination from the nearby magnetar. We only extract events within the 2–8 keV range to minimize photons from the diffuse X-ray background (e.g., Neilsen et al. 2013). An aperture of radius 10″ is centered on 17°45′00″, −28°59′52″ as the background region. The CSC is used to check for known sources within this area. No obvious point or extended sources are in this region that would bias our results. A 300 s binning time is adopted following previous light-curve analyses of this source.

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4 The online tool is located at https://astroutils.astronomy.osu.edu/time/bjd2utc.html.
To detect flaring emission, we use an open-source Bayesian Blocks Python module called bbblocks\(^5\) (Scargle 1998; Scargle et al. 2013; Williams et al. 2017) with a false-positive rate of \(p_{0} = 0.05\). The light curves of Sgr A* and the Bayesian Blocks results are shown in Figure 1 (right).

3. Results

The ALMA, Spitzer, and Chandra light curves for these observations all show the presence of flaring emission. Unfortunately, the submillimeter flare peak appears to occur between ALMA execution blocks. However, a sufficient amount of the flare is present to complete cross correlations with the other simultaneous observations. Throughout this paper, we use the pyCCF (Peterson et al. 1998; Sun et al. 2018) Python module with 5000 Monte Carlo simulations to check for possible delays in the peak emission. A histogram of the 5000 centroid lag times is made, and we characterize the spread in the time delay using the 95% (2\(\sigma\)) confidence interval (CI). We consider a statistically significant time lag if 0 is not contained within this interval. The mean and 95% CI error range is denoted on each histogram plot.

We check for, but do not detect, a time delay between the most widely separated ALMA frequencies; the histogram is shown in Figure 2 (left). We find a time delay of \(\centerdot t = 29.95^{+3.45}_{-3.44}\) minutes between the 334 GHz and mid-IR light curves, where the submillimeter emission is lagging (Figure 2, center). As a secondary check, we use the ZDCF cross-correlation code (Alexander 1997) along with the PLIKE program (Alexander 2013) on the submillimeter and mid-IR light curves. We find a time delay of \(\centerdot t = 29.51^{+6.28}_{-6.02}\) minutes, consistent with the value from pyCCF. A close-up plot of these two light curves is shown in Figure 3 (left). However, as the full submillimeter flare was not observed, the measured time delay between the submillimeter and mid-IR is an upper limit to the true value. In this case, the 2\(\sigma\) CI quoted only measures the statistical error of the observed peaks within the photometric uncertainties and does not characterize the systematic error caused by an incomplete light-curve sampling.

\(^5\) The open-source Bayesian Blocks algorithm produced by Peter Williams is located at https://pwkit.readthedocs.io/en/latest/science/pwkit-bblocks/.

Eckart et al. (2008) detected delayed flaring emission at 345 GHz relative to near-IR data on the order of 1.5 ± 0.5 hours. Eckart et al. (2009) lists modeled time delays between the IR to submillimeter/radio bands, which range from 0.3 to 1.7 hours. The time-delay upper limit we calculate between the Spitzer and ALMA data here is well within the range of those previously published in the literature.

We find that the 2–8 keV flare is simultaneous with the mid-IR data using pyCCF (Figure 2, right) and agrees with the ZDCF analysis that we perform (\(\centerdot t = 1.10^{+3.29}_{-1.29}\) minutes). Boyce et al. (2019) analyzed more than 100 hr of simultaneous Spitzer and Chandra data. Their analysis found the X-ray data to lead the IR flaring emission by 10–20 minutes at the 68% confidence level. However, they note the time delays of the detected flares contain 0 at a confidence level of 99.7%. Our cross-correlation results match with this more broad study of IR/X-ray time lags and with the previous analysis of this data (Abuter et al. 2021; H. Boyce et al. 2021, in preparation). Additionally, the observed flaring emission in the Gravity K-(2.2 \(\mu\)m) and H-filters (1.63 \(\mu\)m) are simultaneous with the Spitzer observations (Abuter et al. 2021). The lack of time delay at these higher frequencies matches expectations from the adiabatically expanding picture, where the IR data are optically thin.

As noted above, due to noncontinuous ALMA execution blocks, the true submillimeter flare peak may not have been observed. We use a Bayesian analysis technique known as Gaussian Process Regression from the sklearn Python package (Pedregosa et al. 2011) to interpolate the missing data. Our kernel is a compound radial-basis + constant function, which we use to fit the lowest-frequency ALMA data. In the lower left panel of Figure 3 (right), we show the observed ALMA data (red) and the mean Gaussian process fit (black). The shaded purple region is the 95% CI of the fit. We complete a cross correlation between ALMA and Spitzer using pyCCF with the Gaussian-process-fitted data, and their 68% (1\(\sigma\)) CI errors appear to be consistent with the analysis above. The cross-correlation histogram is shown in the right panel, where we find \(\centerdot t = 24.04^{+1.60}_{-1.50}\) minutes.

Both methods find evidence for time-delayed emission between the peaks of the submillimeter and mid-IR data. Neither technique can determine if the delay is conclusive,
Figure 3. Left: close-up plot of ALMA (blue) and Spitzer (red) flaring emission detected on this night of observation. Right: the cross-correlation analysis between the Spitzer data and Gaussian-process-regressed ALMA light curve. In the bottom left panel, the solid black line represents the mean Gaussian process light curve, and the shaded purple region is the 95% CI for the regressed data. The right panel shows the cross-correlation histogram between the two light curves.

however. The three test models presented by Abuter et al. (2021) are not able to produce time-delayed emission, which is indicative of an optically thick and dynamically evolving source, nor can it match the observed peak 334 GHz indicative of an optically thick and dynamically evolving source, nor can it match the observed peak 334 GHz.

4. Analysis

In Section 3, we applied two different methods to check the observed time delay between the submillimeter and mid-IR light curves. However, the gap in our submillimeter data near the peak allows for a range of possible conditions, namely, both simultaneous and time-delayed emission relative to the mid-IR data. If the submillimeter emission is time delayed, the total peak flux is approximately 5.5 Jy (requiring a peak flare flux ≳0.9 Jy). If the emission is simultaneous, the total flux is ≈6 Jy with a peak flare flux of ≈1.4 Jy. This latter value is estimated using a linear extrapolation of the submillimeter data between $t = 3:36:00-4:12:00$ hr UTC. Note that peak flare fluxes for the simultaneous and time-delayed cases were calculated assuming a quiescent flux of ≈4.6 Jy, approximated from the ALMA light curve.

4.1. Can the Gravity Model Reproduce the Submillimeter Emission?

We focus on the parameters of the synchrotron model PLCool$^{−\tau_{\text{max}}}$ (PLC) as described by Abuter et al. (2021), which they note are their best-fitting model. With no knowledge of the submillimeter emission, a synchrotron-powered flare (with a cooling break and high-energy cutoff) can describe the IR and X-ray data. However, our analysis above shows a nonzero time-delay upper limit between the mid-IR and submillimeter bands. In this case, a pure synchrotron model is insufficient to describe the submillimeter emission.

The flare detected using Spitzer at 4.5 μm had a reddened-corrected flux of approximately 20 mJy. The corresponding Gravity K- and H-filters both observed reddened-corrected fluxes of nearly 15 mJy. This is consistent with an electron power-law index of $p = 2$ ($N(E) \propto E^{−p}$) and implies an IR spectrum of $S_{\nu} \propto \nu^{−0.5}$. The other two parameters in their model are the radius of the flaring region and magnetic field strength, for which they choose 1 $R_\odot$ (Schwarzschild radius) and 30 Gauss, respectively. For $M_{\text{BH}} = 4.297 \times 10^6 M_\odot$, 1 $R_\odot = 1.27 \times 10^{12}$ cm.

We use these parameters in the context of the adiabatic expansion picture to determine the submillimeter emission. For a spherical region emitting synchrotron radiation, the observed flux ($S_0$), radius ($R_0$), and optical depth ($\tau_0$) at frequency $\nu_0$ are related by

$$S_0 = \frac{\pi R_0^2}{d^2} J_0(1 - e^{-\tau_0}).$$

$d$ is the distance to the Galactic Center, and $J_0$ is the source function of a power-law synchrotron source, which is a function of $p$, $\nu_0$, and $B$. Solving for the mid-IR optical depth yields $\tau_{\text{IR}} = 1.36 \times 10^{-8}$. In the adiabatic picture, $p$ and the critical optical depth (where the plasma blob becomes optically thin), $\tau_{\text{crit}}$, are related via

$$e^{\tau_{\text{crit}}} - \left(\frac{2p}{3} + 1\right)\tau_{\text{crit}} - 1 = 0$$

(Yusef-Zadeh et al. 2006). The flux and opacity at any radius $R$ and frequency $\nu$ are determined by

$$S_{\nu}(R) = S_0 \left(\frac{\nu}{\nu_0}\right)^{5/2} \left(\frac{R}{R_0}\right)^{3} \frac{1 - e^{-\tau_{\nu}}}{1 - e^{-\tau_0}}.$$

and

$$\tau_{\nu}(R) = \tau_0 \left(\frac{\nu}{\nu_0}\right)^{-0.5} \left(\frac{R}{R_0}\right)^{-(2p+3)}.$$

With $\tau_{\text{IR}} = 1.36 \times 10^{-8}$, $\nu_0 = 66.6$ THz ($c/\nu_0 = 4.5 \mu m$), $p = 2$, $R = R_\odot$, and a critical optical depth of $\tau_{\text{crit}} = 1.51$, the submillimeter opacity at 334 GHz is $\tau_{\text{submm}} = 0.11$. Since $\tau_{\text{submm}} < \tau_{\text{crit}}$, the submillimeter emission is optically thin and expansion cannot produce a time-delayed submillimeter flare, these parameters produce a submillimeter peak that is simultaneous with the mid-IR. At 334 GHz, the peak flare flux is 0.27 Jy, which underestimates the submillimeter peak flux by a factor of ≈2. Therefore, we consider models with steeper spectra ($p > 2$), and use the adiabatic expansion model to calculate physical parameters consistent with the submillimeter
and IR data in both cases of simultaneous and time-delayed emission.

4.2. Case 1: Optically Thin Submillimeter Emission

The choice of $p$ will affect if the submillimeter emission is delayed relative to the mid-IR. Additionally, it will influence physical parameters such as the equipartition magnetic field strength, cooling time, and initial radius. We show how these parameters depend on $p$ in Figure 4 (left). In these illustrative calculations, we assume the peak flare fluxes at 334 GHz and 4.5 $\mu$m are 1 Jy and 20 mJy, respectively. When calculating the equipartition magnetic field strength, $B_{eq}$, we assume the electron power-law index is valid between energies of 10 MeV to 1 GeV ($20 \leq \gamma_e \leq 2000$), and neglect the presence of protons or thermal electrons. To calculate the expansion velocity and velocity-dependent parameters (such as the time delay) in Figures 4 and 5, we use a 15 minute decay timescale. This
timescale is estimated from the submillimeter flare’s decay rate (Figure 3, left) instead of the less-certain submillimeter/IR time delay.

In the optically thin case, the flare submillimeter-to-IR spectrum is consistent with $S_{\nu} \propto \nu^{-0.75}$ (using the peak flare fluxes at 4.5 μm and 334 GHz noted above). Such an optically thin spectrum is produced when $p = 2.5$. For this value for $p$, the equipartition magnetic field strength is $B_{\text{eq}} \approx 27$ Gauss with an initial radius of $R \approx 2 \, R_{S}$. These parameters predict K- and H-filter peak fluxes of $\approx 12$ mJy and $\approx 9$ mJy, respectively (Figure 4, right). The K-filter flux is close to the observed value, but the H-filter flux is underestimated. This is possibly due to a systematic error in the marginal H-filter uncertainty estimate (Abuter et al. 2021). However, the spectrum may flatten between the submillimeter and IR as it does between the IR and X-ray (Abuter et al. 2021).

The synchrotron cooling time for the electrons dominating the submillimeter emission exceeds 2 hr, much longer than the observed flare lifetime, suggesting that the submillimeter decay is either due to the escape of synchrotron-emitting electrons from the source region or by adiabatic cooling as the region expands. We focus on the latter scenario here as it leads to testable predictions; the former possibility is poorly constrained. A factor of 2 decline in the flare flux occurs over approximately 15 minutes. With $S_{\nu}(t) \propto R^{-2.5}/R^{-5}$ in the optically thin case, we estimate an expansion velocity $v_{\text{exp}} = (2/3) - 1)R_{S}/(900 \, s) = 0.014 \, c$ at lower frequencies, within the typical range $v_{\text{exp}} = 0.003 - 0.1 \, c$ inferred for previous flares at radio/millimeter frequencies (Yusef-Zadeh et al. 2008). This model cannot explain the $\approx 30$ minute time-delay upper limit between submillimeter and IR wavelengths, but radio/millimeter observations would be delayed (Figure 5, top right).

4.3. Case 2: Time-delayed Submillimeter Emission

For $p \geq 2.8$, $\tau_{\text{submm}}$ at the time of the 4.5 μm peak is high enough to delay the submillimeter peak due to the transition from an optically thick to thin plasma as the synchrotron source expands. For values of $p$ that are just above 2.8, the expansion speed is too slow to match the 30 minute lag upper limit of the 334 GHz light curve relative to the IR (lower left panel of Figure 5). A steeper electron spectrum with $p \approx 3.5$ is preferred to match both the 30 minute time-delay upper limit and the 15 minute decay timescale. Then, $R \approx 0.8 \, R_{S}$, $B_{\text{eq}} \approx 90$ Gauss, and $v_{\text{exp}} \approx 0.004 \, c$. The light curves for the representative radio/millimeter/submillimeter frequencies are shown in Figure 5 (bottom right).

Simultaneous, multiwavelength observations of Sgr A* at all accessible frequencies should not be undervalued. Figure 5 shows that the ambiguity of the models for the submillimeter–IR time delay can be broken by observing at least one lower frequency.

5. Summary and Conclusions

We have reported and analyzed the submillimeter light curve of Sgr A* observed as part of a global multiwavelength campaign on 2019 July 18. We confirm that the mid-IR data, observed with the Spitzer Space Telescope, is simultaneous with soft X-ray emission detected with the Chandra X-ray Observatory. Our analysis finds a time delay between the submillimeter light curve, taken with ALMA, and the Spitzer mid-IR light curve. However, the submillimeter data do not sample the entire flare, so the measured time delay is an upper limit to the true value. We analyze the submillimeter and mid-IR emission using adiabatically expanding synchrotron plasma models. We prefer an electron energy spectrum with $p = 2.5$ if the submillimeter emission is initially optically thin. We do not make conclusions about the electron spectrum at high energies, as a cooling break and high-energy cutoff is preferred (Abuter et al. 2021) but is not modeled here. Since the submillimeter and mid-IR time delay is not certain, we calculate physical parameters of the flaring emission for different values of the electron power-law index, $p$, which cover both optically thick and thin models. If the submillimeter-to-IR time delay is truly absent, an adiabatically expanding plasma with $p = 2.5$, $R \approx 2 \, R_{S}$, equipartition magnetic field strength of $B_{\text{eq}} \approx 27$ Gauss, and expansion speed $v_{\text{exp}} \approx 0.014 \, c$ can model the data. If the submillimeter emission is delayed by 30 minutes relative to the mid-IR, an adiabatically expanding plasma with initial radius $R \approx 0.8 \, R_{S}$, $p = 3.5$, $B_{\text{eq}} \approx 90$ Gauss, and $v_{\text{exp}} \approx 0.004 \, c$ is preferred. In either case, the need for an expanding source region is clear. We showed that multiwavelength observations using at least one lower-frequency band would have been able to break the degeneracy and should be part of future multiwavelength campaigns.

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Software: CASA (McMullin et al. 2007), CIAO, bblocks (Scargle 1998; Scargle et al. 2013; Williams et al. 2017), pyCCF (Peterson et al. 1998; Sun et al. 2018), ZDCF (Alexander 1997), PLIKE (Alexander 2013), sklearn (Pedregosa et al. 2011), Scipy (Virtanen et al. 2020), Jupyter
Notebook (Kluyver et al. 2016), Pandas (McKinney 2010), Matplotlib (Hunter 2007).

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References
Abuter, R., Amorim, A., Bauböck, M., et al. 2021, arXiv:2107.01096
Alexander, T. 1997, in Astronomical Time Series, ed. D. Maoz, A. Sternberg, & E. M. Leibowitz, Vol. 218 (Dordrecht: Kluwer), 163
Alexander, T. 2013, arXiv:1302.1508
Boyce, H., Haggard, D., Witzel, G., et al. 2019, ApJ, 871, 161
Capellupo, D. M., Haggard, D., Choux, N., et al. 2017, ApJ, 845, 35
Dexter, J., Kelly, B., Bower, G. C., et al. 2014, MNRAS, 442, 2797
Dodds-Eden, K., Porquet, D., Trap, G., et al. 2009, ApJ, 698, 676
Eastman, J., Siverd, R., & Gaudi, B. S. 2010, PASP, 122, 935
Eckart, A., Schödel, R., Meyer, L., et al. 2006, A&A, 455, 1
Eckart, A., Baganoft, F. K., Morris, M., et al. 2004, A&A, 427, 1
Eckart, A., Schödel, R., Garcia-Marín, M., et al. 2008, A&A, 492, 337
Eckart, A., Baganoft, F. K., Morris, M. R., et al. 2009, A&A, 500, 935
Evans, I. N., Primini, F. A., Glatfeldt, K. J., et al. 2010, ApJS, 189, 37
Fazio, G. G., Hora, J. L., Allen, L. E., et al. 2004, ApJS, 154, 10
Fazio, G. G., Hora, J. L., Witzel, G., et al. 2018, ApJ, 864, 58
Fritz, T. K., Gillessen, S., Dodds-Eden, K., et al. 2011, ApJ, 737, 73
Gravity Collaboration, Abuter, R., Amorim, A., et al. 2019, A&A, 625, L10
Hora, J. L., Witzel, G., Ashby, M. L. N., et al. 2014, ApJ, 793, 120
Hunter, J. D. 2007, CSE, 9, 90
Kluyver, T., Ragan-Kelley, B., Pérez, F., et al. 2016, in Positioning and Power in Academic Publishing: Players, Agents and Agendas, ed. F. Loizides, B. Schmidt, & I. O. S. Press (Amsterdam: IOS Press), 87
Marrone, D. P. 2006, PhD thesis, Harvard University
McKinney, W. 2010, in Proc. 9th Python in Science Conf., Vol. 445, Austin, TX (Austin, TX: SciPy), 51
McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in ASP Conf. Ser. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127
Mossoux, E., Grosso, N., Bushouse, H., et al. 2016, A&A, 589, A116
Neilsen, J., Nowak, M. A., Gammie, C., et al. 2013, ApJ, 774, 42
Pedregosa, F., Varoquaux, G., Gramfort, A., et al. 2011, JMLR, 12, 2825
Peterson, B. M., Wanders, I., Horne, K., et al. 1998, PASP, 110, 660
Ponti, G., George, E., Scaringi, S., et al. 2017, MNRAS, 468, 2447
Scargle, J. D. 1998, ApJ, 504, 405
Scargle, J. D., Norris, J. P., Jackson, B., & Chiang, J. 2013, ApJ, 764, 167
Subroweit, M., Mossoux, E., & Eckart, A. 2020, ApJ, 898, 138
Sun, M., Grier, C. J., & Peterson, B. M. 2018, PyCCF: Python Cross Correlation Function for reverberation mapping studies, Astrophysics Source Code Library, ascl:1805.032
van der Laan, H. 1966, Natur, 211, 1131
Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, NatMe, 17, 261
Werner, M. W., Roellig, T. L., Low, F. J., et al. 2004, ApJS, 154, 1
Williams, P. K. G., Clavel, M., Newton, E., & Ryzhkov, D. 2017, pwkit: Astronomical utilities in Python, Astrophysics Source Code Library, ascl:1704.001
Witzel, G., Martínez, G., Hora, J., et al. 2018, ApJ, 863, 15
Witzel, G., Martínez, G., Willner, S. P., et al. 2021, ApJ, 917, 73
Yusef-Zadeh, F., Roberts, D., Wardle, M., Heinke, C. O., & Bower, G. C. 2006, ApJ, 650, 189
Yusef-Zadeh, F., Wardle, M., Heinke, C., et al. 2008, ApJ, 682, 361
Zylka, R., Mezger, P. G., & Lesch. H. 1992, A&A, 261, 119
Zylka, R., Mezger, P. G., Ward-Thompson, D., Duschl, W. J., & Lesch, H. 1995, A&A, 297, 83