Near- and Mid-infrared Observations in the Inner Tenth of a Parsec of the Galactic Center Detection of Proper Motion of a Filament Very Close to Sgr A*

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Abstract

We analyze the gas and dust emission in the immediate vicinity of the supermassive black hole Sgr A* at the Galactic center (GC) with the ESO Very Large Telescope (Paranal/Chile) instruments SINFONI and VISIR. The SINFONI $H$+$K$ data cubes show several emission lines with related line map counterparts. From these lines, the Br$\gamma$ emission is the most prominent one and appears to be shaped as a bar extending along the north–south direction. With VISIR, we find a dusty counterpart to this filamentary emission. In this work, we present evidence that this feature could most be likely connected to the minispiral and potentially influenced by the winds of the massive stars in the central cluster or an accretion wind from Sgr A*. To this end, we could the SINFONI data between 2005 and 2015. The spectroscopic analysis reveals a range of Doppler-shifted emission lines. We also detect substructures in the shape of clumps that can be investigated in the channel maps of the Br$\gamma$ bar. In addition, we compare the detection of the near-infrared Br$\gamma$ feature to PAH1 mid-infrared observations and published 226 GHz radio data. These clumps show a proper motion of about $320\,\text{km}\,\text{s}^{-1}$ that are consistent with other infrared continuum–detected filaments in the GC. Deriving a mass of $2.5 \times 10^{-5} \, M_\odot$ for the investigated Br$\gamma$ feature shows an agreement with former derived masses for similar objects. Besides the north–south Br$\gamma$ feature, we find a comparable additional east–west feature. Also, we identify several gas reservoirs that are located west of Sgr A* that may harbor dusty objects.

Unified Astronomy Thesaurus concepts: Interstellar dust extinction (837); Interstellar clouds (834); Galactic center (565); Interstellar dust (836); Interstellar atomic gas (833)

1. Introduction

Investigating the vicinity of supermassive black holes (SMBHs), and in particular the vicinity of the SMBH associated with the compact radio source Sgr A*, is often connected to the investigation of gas and dust on large ($\gg 1\,\text{pc}$) and small scales ($\lesssim 1\,\text{pc}$). This is important if one wants to characterize star formation or to determine the mass of the SMBH itself. In this context, Wollman et al. (1977) used the minispiral gas velocities to derive the Sgr A* SMBH mass. Yusef-Zadeh et al. (1998) and Zhao & Goss (1998) also observed proper motions of gaseous-dusty structures and filaments based on their radio continuum detections in the vicinity of Sgr A* and the Galactic Center (GC) stellar association IRS13E. Mužić et al. (2007) completed that picture by expanding the analysis toward shorter wavelengths in the near-infrared (NIR). These publications derive typical gas and dust filament velocities of several hundred km s$^{-1}$.

However, extragalactic studies of gas and dust on larger scales by Böker et al. (2008) led to the introduction of two models that could describe the feeding process of SMBHs as well as the provision of a gas reservoir that is responsible for star formation: the “popcorn model” and “pears on a string” scenarios. A large amount of the dusty and gaseous material typically accumulates along the ring on the scale of 100 pc and less at the innermost dynamical resonance referred to as the inner or nuclear Lindblad resonance (Fukuda et al. 1998). Böker et al. (2008) discuss two scenarios of star formation along the nuclear ring. The “popcorn model” describes a scenario when the gas is accumulated along the ring rather uniformly so that the critical density is reached throughout the whole ring. As a result, there is no age gradient of star-forming clusters along the ring. The “pears on a string” model operates with the localized burst of star formation in so-called overdensity regions, which can often be associated with the sites where the gas material enters the ring. The star-forming clusters are then formed along the ring in a sequential way that leads to the age gradient. The “pears on a string” scenario is supported by observational data (Böker et al. 2008; Fazeli et al. 2019).

For the GC, Nayakshin et al. (2007) and Jalali et al. (2014) modeled the gravitational influence of the SMBH on molecular clouds on intermediate scales that are moving from a distance of several parsecs toward Sgr A*. Those authors find indications that infalling material could trigger star formation in the close vicinity of the SMBH. On larger scales, this could be linked to the proposed “pears on a string” model. It is evident that the investigation of gas and dust reservoirs located in the inner and outer parsecs contributes to the understanding of star formation (Böker et al. 2008; Jalali et al. 2014) and black hole feeding.

A key question is how the material is transported from the larger scales all the way to Sgr A*. An occasional collision of clumps inside the circumnuclear disk (CND), which is located between 1.5 and 7 pc, can lead to the loss of angular momentum and the formation of streamers that are tidally interacting with the SMBH—the minispiral streamers can be the manifestation of this process (Jalali et al. 2014). Another way to fill the central cavity inside the CND is the interaction of stellar winds with the inner rim of the CND, which can also lead to the formation of infalling denser clumps that are tidally interacting with Sgr A* (Blank et al. 2016). Finally, thermal instability could have operated in the central parsec during the
phases of enhanced activity of Sgr A*, which would create a multiphase medium where the warm and more diluted plasma material is in approximate pressure equilibrium with the colder and denser gas (Różańska et al. 2014, 2017).

In this work, we investigate the Brγ gas reservoir in the direct vicinity of Sgr A*, the SMBH of our host Galaxy. We use $H+K$ data obtained with SINFONI, a Very Large Telescope (VLT) instrument that is now decommissioned. We investigate the ionized gas located close to the line of sight toward the S-cluster (~0.04 pc) in the channel maps of the related data cubes. Additionally, we connect our detections to the 226 GHz radio observations executed by Yusef-Zadeh et al. (2017a) and mid-infrared (MIR) VISIR data from 2018 to investigate the gas filaments at longer wavelength regimes.

In Section 2, we shortly introduce the methods used for the observations and the analysis of the obtained data. This is followed by Section 3, where we present the results. These results are then discussed in Section 4. In Section 5, we summarize our findings and present our conclusions.

2. Data and Observations

Here, we briefly describe the observations, the data reduction, and the methods that are used for the data analysis.

2.1. SINFONI

The VLT Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) data presented in this work had already been used for Valencia-S. et al. (2015) and Peißker et al. (2019, 2020a, 2020b), and are described there in detail. To provide a complete picture about the analysis, the data are listed in Appendix C. The observations were carried out at the UT4/VLT (Paranal, Chile). For the spectroscopic analysis, we use data cubes between 2005 and 2015 centered on Sgr A* in order to ensure an adequate S/N. For determining the proper motion, we include also the data cube of 2018 to increase the baseline for the analysis. The position of Sgr A* is determined through its offset from the star S2, for which we know the orbital elements very well (see Parsa et al. 2017; Gravity Collaboration et al. 2019). Here, in particular, we investigate the line emission of the Brγ gas distribution and the channel maps of the SINFONI $H+K$ data cubes. An image of the Brγ line flux and the related $H+K$-band spectrum are shown in Figure 1.

2.2. VISIR

The mid-infrared spectrometer and imager (VISIR) is mounted at the ESO UT2 (UT3 at the time of the observation). We used the smallest field of view (FOV) with a spatial pixel size of 0′′.045 and a total image size of $38.0′′ \times 38.0′′$ per image in the N-band PAH1 filter (8.59 μm). To increase the signal-to-noise ratio (S/N), we shift and add the single images to create a $40′′ \times 40′′$ overview image. We used the standard calibration files that are provided within the ESO pipeline. To suppress the background, differential observations with the chop/nod mode of VISIR are executed. This allows tracing faint point sources—and in particular, extended features at this wavelength. The observation was executed in 2016 and is part of a larger survey (N. B. Sabha et al. 2020, in preparation).

3. Results

In this section, we will show the results of the GC observations with SINFONI and VISIR. The bar-like structure of the Brγ distribution and additional gas reservoirs can be observed in the SINFONI $H+K$ channel maps and with the VISIR PAH1 filter. We compare these features to structures detected in the 226 GHz radio domain by Yusef-Zadeh et al. (2017b).

3.1. Spectral Emission Lines

Here, we present the results of the spectral line analysis of the bar that is shown in Figure 1. We spatially select the feature in the data cube for which its spectrum shows [Fe II], Brγ, Brδ, He I, H2S(1), H2S(0), some CO features, and H2Q(1) line emission. Since not every line reveals a strong counterpart in its emission in the corresponding channel maps, we emphasize the investigation of the Brγ, Brδ, He I, [Fe II], and H2S(0) emission (see Table 1). These lines show clearly identifiable flux distributions and can be safely related to ionized emission of a gaseous bar (see Figure B1). The blueshifted H2S(0) emission line seems to be an outlier. Even though we detect extended related H2S(0) line emission that can be clearly connected to the Brγ bar, the Doppler-shift of this distribution indicates the presence and contribution of embedded and/or background/foreground objects (see the discussion in Section 4.6). For the sake of completeness, the line is still listed in Table 1.

We find that the hydrogen recombination lines lie at a velocity of about 50–60 km s$^{-1}$ and the lines that stand for a higher excitation ([Fe II] and He I) are at a higher velocity of about 120–140 km s$^{-1}$. This may indicate that the hydrogen lines trace the bulk of our bar feature whereas the higher excitation lines may be linked to a wind phenomenon (acting at its surface), resulting in a slightly higher redshift.

For the He I/Brγ ratio, we find a value of 0.7, which is in agreement with the ratios of (0.35–0.7) observed in the GC (Gillessen et al. 2012). Compared to the surrounding Brγ emission extended on larger scales, the intensity of the line at the position of the bar and especially of the clump-like

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5 SINFONI was decommissioned at the end of 2019 June.
6 Program ID: 097.C-0023.
enhancements therein varies by around 10%. We therefore derive a He I/Brγ ratio of 0.7 ± 0.1.

The extended Brγ line emission as well as the MIR PAH1 continuum image (see Section 3.5) of the central few arcseconds clearly show a north–south as well as an east–west feature. Both contain substructures, which are discussed in the following sections.

3.2. Substructures of the North–South Brγ Bar

In Figure 1, we show a K-band image and a Brγ channel map that is extracted from the combined data cube that covers data sets obtained over a period of almost 10 yr. The expected smearing effect due to proper motions of the features is significantly smaller than their extent and is eliminated by centering the individual data cubes on the position of Sgr A*.

Around 400 data cubes with a single exposure time between 400 and 600 s are used. With the clear detection of clumps (in the following indexed by cl) in the extended Brγ features, we can determine the filling factor f of these components as derived by

\[ f = f_\infty + (1 - f_\infty) \exp \left( -\frac{\nu}{v_{cl}} \right). \]

This equation is introduced by Hillier et al. (2003). The authors use it to derive the filling factor for clumps that are created in the winds of two O-stars with a shared age of around 4.4 Myr in the Small Magellanic Cloud. Strong winds also prevail in the central region of the GC stellar cluster; in combination with the recent publication by Calderón et al. (2020a), this justifies the use of Equation (1). An effective use of the filling factor is described by Yusef-Zadeh et al. (2013), where the authors derive the number of clumps via \( n_{cl} = f/(4/3\pi r^3) \). For \( f = 1 \), there would be no clumping. It is obvious that a filling factor \( f_\infty \) for the Brγ bar far away from the observed emission is not equal to 1, but rather lower values. Therefore, we assume an upper limit for \( f_{\infty, up} = 0.9 \) and a lower limit of \( f_{\infty, low} = 0.1 \).

Table 1

| Spectral Line (@rest Wavelength (μm)) | Central Wavelength (μm) | Velocity (km s⁻¹) |
|--------------------------------------|------------------------|------------------|
| [Fe II] @1.64400 μm                  | 1.64476 ± 0.00022      | 138.68 ± 40.14   |
| Brδ @1.94509 μm                     | 1.94548 ± 0.00010      | 60.15 ± 15.42    |
| He I @2.05869 μm                    | 2.05951 ± 0.00017      | 119.49 ± 24.77   |
| Brγ @2.16612 μm                     | 2.16650 ± 0.00010      | 52.62 ± 15.42    |
| H2S(0) @2.22329 μm                  | 2.21923 ± 0.00030      | −547.83 ± 40.48  |

Note. The related spectrum is shown in Figure 1.
for equation Equation (1). For $n_{cl} = 2 - 4$, we derive values for $f$ close to 0.5.

The derived velocity $v_{cl}$ of the clumps in the Brγ bar are based on the line-of-sight (LOS) velocity presented in Table 1. Mužić et al. (2010) state that the wind velocity $v$, prevailing in the S-cluster region, is about 750 km s$^{-1}$, which is consistent with wind values derived by Najarro et al. (1994). With that, we derive an average filling factor of $f_{avg} = 0.5$. From Gillessen et al. (2012), we use for the case B recombination of Brγ:

$$\rho_{cl} = 2.6 \times 10^3 \left( \frac{f}{0.5} \right)^{-\frac{1}{2}} \left( \frac{R}{3 \text{ mpc}} \right)^{-\frac{1}{2}} \times \left( \frac{T}{10^4 \text{ K}} \right)^{0.54} \text{ cm}^{-3},$$

where $\rho_{cl}$ donates the clump density. Following the analysis of Gillessen et al. (2012), we adapt the assumed electron temperature of $10^4$ K (see also Zhao et al. 2009). With a radius of 75 mas/clump (≈3 mpc/clump) in the Brγ bar, we get a mass per clump of

$$M_{cl} = 1.7 \times 10^{28} \left( \frac{f}{0.5} \right)^{-\frac{1}{2}} \left( \frac{R}{3 \text{ mpc}} \right)^{-\frac{1}{2}} \times \left( \frac{T}{10^4 \text{ K}} \right)^{0.54} \text{ g/cl} \approx 2.1 M_{\odot}/\text{cl}.$$ 

Since we detect around four individual clumps with comparable properties in the SINFONI FOV, we derive a lower limit for the mass of the observed Brγ-bar clumps of $8.4 M_{\odot}$ or $2.5 \times 10^{-5} M_{\odot}$. From the HeI/Brγ ratio $\eta$, we get $\eta \approx 0.7$. The Brγ emission feature is obviously not homogeneous, as can be seen in Figure 1. In order for the presumably thin material to reproduce the line ratio $\eta$, the former derived volume filling factor of $\leq 0.5$ is justified.

### 3.3. Substructures of the East–West Brγ Bar and Additional Gas Reservoirs

Only the SINFONI data set of 2005 covers the area west of Sgr A*. Because of the limited data quality, we smooth the Brγ line map with a 6 px Gaussian. Apart from the Brγ Bar, we find several other gas reservoirs west of Sgr A* in different shapes. We name the detected features L0–L4 (see Figure 2). Because these gas reservoirs are also seen in our VISIR continuum data (see Section 3.5), we are confident that the Brγ gas emission areas are not remnants of the continuum subtraction. Peißker et al. (2020b) show several dusty sources with a presumably stellar core at the position of the Brγ features L0 and L1. Both features show an angular difference of $\Delta = 60^\circ$. Compared to the 226 GHz radio map presented by Yusef-Zadeh et al. (2017b), we find related counterparts to both L0 and L1. We speculate that also the additional gas and dust reservoirs associated with L2—L4 (see Figure 2) will contain compact dusty sources or young stellar objects.

### 3.4. Proper Motion

By comparing the line maps of the Brγ Bar that are centered on Sgr A*, a proper motion can be derived (Figure A1). As indicated by the contour maps shown in Figure 1, we emphasize the analysis of the more prominent upper part of the Brγ Bar. To obtain the proper motion of this prominent part, we use a cross-correlation method and additionally two Gaussian fitting methods (Figure 3). For the former method, we shift the Brγ line map of 2018 to the 2006 position of the Brγ Bar and record at which shifting vector the emission reaches its maximum. The shifting vector is then equivalent to the distance that the feature moved projected on the sky. We find a proper motion of $329 \pm 20 \text{ km s}^{-1}$ directed westward.

Since the Brγ line flux distribution shows substructures (four clumps; see Figure 1), fitting a Gaussian to different substructures gives a complementary estimate of the velocities (see Table 2 for the derived distances). From this, we get velocities for R.A. and decl. that are based on the fit parameters (Figure 3). The resulting proper motion is $319 \pm 44 \text{ km s}^{-1}$ directed westward. For the sake of completeness, we fit a Gaussian to the prominent upper part in 2006 and 2018. We crop the lower part of the data cube to exclude extra emission. This results in a proper motion of $293 \pm 60 \text{ km s}^{-1}$. The error includes different background scenarios, a variation of data quality, and emission that might be suppressed due to stellar emission lines.

Combining all three velocities, we get $314 \pm 41 \text{ km s}^{-1}$ for the prominent upper part of the Brγ bar. Using a Gaussian fit to substructures and the complete lower part, we derive a total proper motion of $305 \pm 15 \text{ km s}^{-1}$. In contrast, the proper motion vector of the lower part of the Brγ bar points south while the upper part is directed west. Consult Table 3 for the individual R.A. and decl. proper motion velocities.

### 3.5. Mid-infrared Detection

Based on the 2016 VISIR data set, we find at the position of the Brγ Bar in the N band a PAH1 (8.59 $\mu$m) counterpart with a width of 0.4 $\mu$m. The substructures shown in the contour plot in Figure 1 are indicated in the low-pass filtered cutout on the right-hand side of Figure 4. The size of the Brγ line flux distribution is in good agreement with the PAH1 detection. The angular difference between the L1 to L0 component is $\Delta = 60^\circ$ and consistent with the Brγ-bar orientation (Figure 2). Because the FOV of SINFONI is limited, we find a small size difference of around 10%–15% compared to the VISIR detection, which is already included in the uncertainties of the analysis presented here. While the size of the Brγ Bar in our SINFONI data can be determined to be around 0.095, the PAH1 continuum counterpart observed with VISIR extends over 11'.

### 3.6. The 226 GHz Radio Detection

The Brγ features close to the line of sight toward Sgr A* can also be identified in the radio. Here, we refer to the radio maps published by Yusef-Zadeh et al. (2017a), and in particular to their Figure 2, where the authors show several linear ridge components. Unfortunately, the Brγ features are very close to the Sgr A* position, such that the corresponding identification can only be made via elongations on the lowest contours of the Sgr A* point source response.

In our Figure 2, we compare the smoothed Brγ map with the radio map. In Table 4, we list the components’ names, the relative coordinates, and their 226 GHz fluxes. We identify the northern and southern radio extensions marked EN and ES with the northern and southern tip of the north–south (NS) Brγ feature. The western Brγ feature can be identified as the
extension labeled L1. It is followed by the curved source complex labeled L2 and the extended (0"15 to 0"2 diameter) sources L3 and L4. The 226 GHz radio flux density of these components can be estimated from their extent and the contour line labels given in Figure 2 by Yusef-Zadeh et al. (2017a). The east–west linear feature L1 appears to arise from Sgr A*. Yusef-Zadeh et al. (2017a) point out that it coincides with the diffuse X-ray emission and a minimum in the near-IR extinction. They argue that the millimeter emission is produced by synchrotron emission from relativistic electrons in equipartition with an ~1.5 mG magnetic field.

Table 2

| Year | R.A. in (mas) | Decl. in (mas) | ΔR.A. in (mas) | ΔDecl. in (mas) |
|------|---------------|----------------|----------------|-----------------|
| 2006 | 180.50        | 302.16         | ...            | ...             |
| 2007 | 193.62        | 311.12         | 13.12          | 8.96            |
| 2008 | 191.16        | 311.88         | 10.66          | 9.72            |
| 2010 | 211.87        | 322.00         | 31.37          | 19.84           |
| 2011 | 210.25        | 316.37         | 29.75          | 14.21           |
| 2012 | 206.87        | 305.37         | 26.37          | 3.21            |
| 2015 | 237.37        | 326.37         | 56.87          | 24.21           |
| 2016 | 248.62        | 302.87         | 68.12          | 0.71            |

Note. We measured the distance by using the substructures of the prominent upper part of the bar. The traveled distance ΔR.A. and ΔDecl. are related to the distance to 2006. The uncertainty is ±12.5 mas and equivalent to ±1 px.

Table 3

| Method                  | v_{R.A.} (km s^{-1}) | v_{Decl.} (km s^{-1}) | v_{Total} (km s^{-1}) |
|-------------------------|-----------------------|-----------------------|------------------------|
| Cross-correlation (upper part) | 117                   | 307                   | 329                    |
| Gaussian (upper part)   | 163                   | 244                   | 293                    |
| Gaussian (lower part)   | 153                   | 252                   | 295                    |
| Substructures (upper part) | 209                  | 241                   | 319                    |
| Substructures (lower part) | 114                  | 293                   | 314                    |

Note. For fitting a Gaussian to the upper and lower part, we use pixel values between 10 and 12. The clumpy substructures can be fitted with an 5–6 px Gaussian. Note that we shift the data cubes of 2006 and 2018 for the cross-correlation only in R.A. direction. Typical uncertainties for v_{Total} are in the order of ±40 km s^{-1}, for v_{R.A.}/v_{Decl.} around ±20 km s^{-1}.
Yusef-Zadeh et al. (2017a) argue that the linear ridge may become brighter close to the peak of Sgr A* at 226 GHz and may therefore have a hard or highly inverted spectrum because there is no detectable emission of it at lower frequencies. However, at lower frequencies, the beams typically become larger and sources close to Sgr A* are more difficult to detect. Hence, the scenario could also be compatible with a flat-spectrum Bremsstrahlung source.

Yusef-Zadeh et al. (2017a) point out that in the recent milliarcsecond resolution, the 86 and 230 GHz observations of Sgr A* show indications of an asymmetric source structure (Brinkerink et al. 2016; Fish et al. 2016). Toward the east under a position angle of about 90°, a secondary source shifted by 100 μas from Sgr A* is indicated by the data. While this could be explained by interstellar scattering (Brinkerink et al. 2016), intrinsic source properties could be responsible as well. However, given the proper motion of the ridge component L0 in the order of 320 km s⁻¹, it is very likely that it is part of the minispiral gas flow. Given that L1 is comparable in shape and size to L0, it is very likely that the east–west feature could also be part of this gas flow.

Assuming an optically thin free–free emission spectral index of 0.1 between 5 and 226 GHz and an intrinsic Brγ/Brα ratio of 2.8, we can estimate the expected Brγ line intensity from the 226 GHz radio continuum flux density using the formula (Glass 1999)

\[
I(\text{Brγ}) = 1.42 \times 10^{-17} \left( \frac{T}{10^4 \text{ K}} \right)^{-0.85} \left( \frac{\nu}{226 \text{ GHz}} \right)^{0.1} F_r(\text{mJy}) \text{ W m}^{-2}.
\]  

We then compare the predicted flux density \( I(\text{Brγ}) \) to the observed flux density that is based on the SINFONI Brγ line map detection. These maps are related to the channels 1515–1520 that corresponds to 2.16527 and 2.16825 μm. From the ratio of the expected to observed flux density, we obtained an estimate of the extinction in the minispiral region at 2.16 μm. The results are listed in Table 2.

The observed extinction ranges from 2.5 to 3.2 mag, with an averaged extinction of 2.91 ± 0.72 mag (see Table 4). This is in good agreement with Schödel et al. (2010), who reported a median extinction value of \( A_K = 2.74 \pm 0.30 \text{ mag} \) in the range of 1.8–3.8 mag in the minispiral arms, using \( H–K \) colors.

4. Discussion

In this section, we will discuss the results of our analysis. We also link the observed filaments to large-scale features in the region.

4.1. Distance Estimate of Brγ Bar and Its Stability in the Hot Bubble

Based on the tangential velocity of \( v_t \sim 314 \text{ km s}^{-1} \) and the radial velocity of the bar \( v_r \sim 53 \text{ km s}^{-1} \) (based on the Brγ emission line), we estimate the total space velocity using \( v_{\text{bar}} \sim (v_t^2 + v_r^2)^{1/2} \sim 318 \text{ km s}^{-1} \). From this, we may approximately calculate the distance from Sgr A* assuming a bound circular orbit, \( r_{\text{bar}} \sim GM_*/v_{\text{bar}}^2 \sim 0.17 (M_*/4 \times 10^6 \text{ M}_\odot)(v_{\text{bar}}/318 \text{ km s}^{-1})^{-2} \text{ pc} \sim 4''25 \). If the Brγ were unbound and moving along the parabolic orbit, the distance would be a factor of two larger, \( r_{\text{bar}} \approx 2GM_*/v_{\text{bar}}^2 \sim 0.34 \text{ pc} = 8''75 \). In the following discussion, we...
assume the bar is bound—and hence the smaller distance estimate apply.

The associated orbital (dynamical) timescale is \( t_{\text{dyn}} \sim 2\pi \left[ r^3/(GM) \right]^{1/2} \sim 3300 \text{ yr} \). This applies for the more prominent westward-moving upper part of the Br\(\gamma\) bar. Additionally, we derive similar values for the southward-moving lower part of the bar: specifically, we determine \( r_{\text{bar}} \sim 0.18 \text{ pc} \) and \( t_{\text{dyn}} \sim 3600\text{ yr} \).

With \( r_{\text{bar}} \sim 0.17 \text{ pc} \), the Br\(\gamma\) bar is located at or just beyond the Bondi radius, \( r_{\text{Bondi}} \sim G M_{\odot}/c_s^2 \), where \( c_s \) is the sound speed of the hot gas that is fueled mostly by OB stars. This hot plasma has a temperature of \( T_{\text{Bondi}} \sim 10^7 \text{ K} \) and number density of \( n_{\text{Bondi}} \sim 26 \text{ cm}^{-3} \), from which \( r_{\text{Bondi}} \sim 4''(T_{\text{Bondi}}/10^7 \text{ K}) \sim 0.16 \text{ pc} \) (Baganoff et al. 2003; Wang et al. 2013). In terms of stellar populations, the Br\(\gamma\) bar can be found at larger scales than the S-cluster (1'' \sim 0.04 \text{ pc} ), potentially within the Clockwise Disk of young massive OB stars located between 0.032 and 0.48 \text{ pc} (Barko et al. 2009). The derived distance is also comparable to the pericenter distances of the Northern and the Eastern Arm streamers of the minispiral (Zhao et al. 2009), \( r_{\text{peri}} \sim 0.17 \text{ pc} \) and \( q_{\text{peri}} \sim 0.25 \text{ pc} \), respectively, which raises the possibility that the Br\(\gamma\) bar is a detached minispiral material that appears to be positioned close to Sgr A*, just in projection. The Br\(\gamma\) bar could also have originated in the collision site of the Northern and the Eastern Arm, referred to as the Bar, located at \( \sim 0.1-0.2 \text{ pc} \) south of and behind Sgr A* (Zhao et al. 2010).

When one compares the gas pressure of the bar, \( P_{\text{bar}} = n_{\text{bar}} k_B T_{\text{bar}} \sim 2.6 \times 10^{-9} \text{ erg cm}^{-3} \sim 1.38 \times 10^{-16} \text{ erg K}^{-1} \times 10^4 \text{ K} \sim 3.588 \times 10^{-7} \text{ erg cm}^{-3} \), with the pressure of the bremsstrahlung plasma at the Bondi radius, \( P_{\text{Bondi}} = n_{\text{Bondi}} k_B T_{\text{Bondi}} \sim 26 \text{ cm}^{-3} \times 1.38 \times 10^{-16} \text{ erg K}^{-1} \times 10^7 \text{ K} \sim 3.588 \times 10^{-8} \text{ erg cm}^{-3} \), we see that the bar pressure is larger than the pressure at the Bondi radius by one order of magnitude. This implies that the bar is not confined by the surrounding thermal pressure. In that case, the bar expands with a velocity approximately equal to its sound velocity, \( v_{\text{exp}} \sim c_{\text{bar}} = [k_B T_{\text{bar}}/(\mu m_H)]^{1/2} \sim 13 \text{ km s}^{-1} \).

Due to the relative motion of the bar and the ambient medium fueled by stellar winds, force arises on the bar because of the ram pressure, \( P_{\text{ram}} = \rho_{\text{Bondi}} v_{\text{rel}}^2 \), where the relative velocity is the vector sum of the bar motion with respect to the stellar wind velocity field. Given \( v_{\text{bar}} \sim 318 \text{ km s}^{-1} \) and the average stellar-wind velocity of \( v_{\text{wind}} = 750 \text{ km s}^{-1} \) (Najarro et al. 1994), we set \( v_{\text{rel}} \sim 10^3 \text{ km s}^{-1} \). The ram pressure then is \( P_{\text{ram}} = \mu \mu_{\text{Bondi}} v_{\text{rel}}^2 = 0.5 \times 1.67 \times 10^{24} \text{ g} \times 26 \text{ cm}^{-3} \times (10^8 \text{ cm s}^{-1})^2 \sim 2.2 \times 10^{-7} \text{ erg s}^{-1} \). The ram pressure is of an order of magnitude comparable to that of the thermal pressure of the Br\(\gamma\) bar, and hence can confine the bar externally—or at least influence its further evolution.

Moreover, dynamically important magnetic field in the vicinity of Sgr A* can affect the evolution of Br\(\gamma\) bar more than the combined effect of the ram pressure and the external thermal pressure. The magnetic pressure can be estimated from the Faraday rotation measurements of the magnetar PSR J1745–2900, which is located at a distance comparable to that of the Br\(\gamma\) Bar, \( r \sim 0.12 \text{ pc} \) from Sgr A*. The Faraday rotation measurements indicate a line-of-sight component of the magnetic field of \( B \gtrsim 8 \text{ mG} \) (Eatough et al. 2013), from which the magnetic pressure can be estimated as \( P_{\text{mag}} = B^2/8\pi \sim 2.6 \times 10^{-6} \text{ erg cm}^{-3} \) and we see that \( P_{\text{mag}} > P_{\text{ram}} \). It is currently premature to say whether the Br\(\gamma\) Bar belongs to the type of filamentary structures such as nonthermal filaments that follow the global magnetic field lines. Morris et al. (2017) reported on the thin filamentary structure to the north and the east of Sgr A*, the so-called Sgr A West Filament (SgrAWF). In their radio images at centimeter wavelengths, along with a Paro image, one can also see the potential counterparts of the L0–L4 complex to the west of Sgr A*. For the moment, we hypothesize that the Br\(\gamma\) Bar reported here could be the manifestation of minispiral material that is shaped and dynamically affected by the global poloidal magnetic field in a manner similar to SgrAWF, or by the external magnetohydrodynamic drag. However, more multiwavelength data are necessary before definite conclusions can be made. We discuss more mechanisms responsible for clumpy filamentary structures in the GC region in the following subsections.

The bar as a whole will inevitably tend to be tidally stretched because its number density expressed by Equation (2) is five orders of magnitude smaller than the Roche condition of the self-gravitational collapse derived for fully ionized plasma at
the estimated distance of the bar,
\[ n_{\text{bar}} \ll n_{\text{Roche}} \]
\[ = 4.73 \times 10^9 \left( \frac{M_*}{4 \times 10^6 M_\odot} \right) \left( \frac{r}{0.17 \text{ pc}} \right)^{-3} \text{ cm}^{-3}. \]  
(5)

In addition, the tidal radius \( r_t \) for the bar half-length of \( R_{\text{bar}} \sim 0.5 \pm 0.02 \text{ pc} \) (based on SINFONI and VISIR), the estimated bar mass of \( m_{\text{bar}} \approx 2.5 \times 10^7 M_\odot \), and the Sgr A* mass of \( M_* = 4 \times 10^6 M_\odot \) are
\[ n = \frac{2M_*}{R_{\text{bar}}^3} \left( \frac{m_{\text{bar}}}{2.5 \times 10^5 M_\odot} \right)^{1/3} \text{ pc}. \]  
(6)

Hence, the bar is prone to complete tidal disruption because it moves around Sgr A* at \( r \approx 0.2 \text{ pc} \), which is three orders of magnitude closer than \( r_t \). One still cannot exclude the possibility that the Brγ bar is a filamentary, clumpy structure, that is being tidally disrupted overall, but individual clumps would be self-gravitating with number densities on the order of the Roche critical density (see Equation (5)). These clumps would, however, have to be very compact, with length scales of a few au, which follows from the Hill radius:
\[ r_{\text{Hill}} = r_{\text{bar}} \left( \frac{m_{\text{cl}}}{3M_*} \right)^{1/3} \]
\[ = 3.13 \left( \frac{r_{\text{bar}}}{0.17 \text{ pc}} \right) \left( \frac{m_{\text{cl}}}{2.1 M_\odot} \right)^{1/3} \text{ au}. \]  
(7)

Individual clumps could also hide stars that would be enshrouded in optically thick gaseous-dusty shells with a length scale of \( r_{\text{Hill}} \sim 153 \text{ au} \) (Zajaček et al. 2014, 2017; Valencia-S. et al. 2015; Shahzamanian et al. 2016), which follows directly from Equation (7) for \( m_{\text{cl}} = 1 M_\odot \). However, any association of the Brγ bar with the population of dust-enshrouded objects (Ciurlo et al. 2020; Peißker et al. 2020b) is currently speculative and requires additional monitoring of the dynamics of this Brγ complex.

For estimating the lifetime and the stability of the Brγ bar, we follow Burkert et al. (2012), who derived basic timescales for the interaction of a colder clump (in our case, a filament or a streamer) with the surrounding hot medium. The ablation of material due to the motion through the hot medium is rather slow, with an ablation timescale of
\[ \tau_{\text{abl}} = \frac{R_{\text{bar}}}{0.25 q_{\text{abl}} v_{\text{bar}}} \rho_{\text{Bondi}} m_{\text{bar}} \approx 6 \times 10^8 \left( \frac{R_{\text{bar}}}{0.02 \text{ pc}} \right) \]
\[ \times \left( \frac{v_{\text{bar}}}{318 \text{ km s}^{-1}} \right)^{-1} \left( \frac{\rho_{\text{Bondi}}}{10000} \right) \text{ yr}, \]  
where we considered \( q_{\text{abl}} \approx 0.004 \). The evaporation due to thermal conduction proceeds much faster. In the saturation limit and assuming pressure equilibrium (which may not apply, as we estimated earlier), we obtain
\[ \tau_{\text{evap}} \approx 177 \left( \frac{r_{\text{bar}}}{0.17 \text{ pc}} \right)^{1/6} \left( \frac{m_{\text{bar}}}{2.5 \times 10^{-5} M_\odot} \right)^{1/3} \text{ yr}, \]  
(9)

which is an order of magnitude less than the dynamical timescale of a few thousand years. This implies that the Brγ bar is likely a temporary feature that will not survive long enough to affect the activity of Sgr A*, given that the freefall timescale from \( r_{\text{bar}} \) is
\[ t_{\text{ff}} = \pi \left( \frac{r_{\text{bar}}}{G M_*} \right)^{1/2} \sim 1643 \text{ yr}. \]  
(10)

Due to the velocity shear between the bar and the Bondi plasma, the bar is susceptible to the Kelvin–Helmholtz (KH) instability. The velocity shear can be assumed to correspond to the orbital velocity of the bar, \( v_{\text{shear}} \sim v_{\text{bar}} \sim 318 \text{ km s}^{-1} \). Given the density ratio of \( r = n_{\text{Bondi}} / n_{\text{bar}} \sim 10^{-4} \) between the hot plasma and the bar, the instabilities of the size comparable to individual clumps, \( \lambda_{\text{cl}} \sim 3 \text{ mpc} \), will develop on the timescale of
\[ \tau_{\text{KH}} = \frac{\lambda_{\text{cl}} + r}{v_{\text{shear}} \sqrt{r}} \approx 923 \text{ yr}. \]  
(11)

Hence, KH instabilities with sizes comparable to those of the observed clumps can develop within one orbital (freefall)
timescale, and the observed uneven surface brightness of the Brγ structure may be a manifestation of this process. The magnetic field can, in theory, suppress the formation of Kelvin–Helmholtz instabilities and stabilize the structure, especially if the internal tangled magnetic field is present in the bar structure itself (McCourt et al. 2015). On the other hand, as found in McCourt et al. (2015), the structure would still fragment into clumps that would not mix into the hot medium but rather would comove with it. Hence, the bar would continue to change its appearance and the surface brightness during the timescales derived above.

In summary, the Brγ bar is a temporary feature that will likely disappear within 100–1000 yr due to the combined action of evaporation, tidal stretching, and instability development. Given the estimated distance of the the Brγ bar of \( r_{\text{bar}} \sim 0.2 \) pc from Sgr A*, it is unlikely to affect the activity of the SMBH since the freefall timescale is longer than both the evaporation and the instability timescale. These conclusions could, in principle, be affected by a complicated interplay of different components in the central parsec (minispiral, stars, Sgr A*, dust). For instance, if the bar was formed due to the stellar wind–wind collisions as modeled by Calderón et al. (2016, 2020a), the structure can be continuously recreated and/or formed elsewhere, depending on the spatial distribution of stars inside the nuclear star cluster. However, Calderón et al. (2020b) analyzed the cold clump formation via the nonlinear thin shell instability in the wind–wind interaction and found a small mass of individual clumps in the range of \( \sim 10^{-3} \text{–} 10^{-2} M_\odot \), which is much smaller than the mass of a few Earth masses inferred for the clumps along the bar. This makes the association of the Brγ bar with the minispiral streams more likely, because the northern and eastern streamers alone contain \( \sim 12 M_\odot \) of ionized gas (Zhao et al. 2010). We will discuss the relation of the bar to other structures in the GC region in the following subsections.

4.2. Thin Filaments of the GC

As shown by Mužić et al. (2007), elongated and narrow filaments in the vicinity of Sgr A* seem to be the rule and not the exception (see also Ciurlo et al. 2014, 2019).

Even on larger scales compared to the observations presented in Mužić et al. (2007), filaments with a specific orientation with respect to the central region associated with Sgr A* can be observed. Examples are presented, e.g., in the inner \( 1^\circ \times 1^\circ \) by LaRosa et al. (2004). Here, the authors characterize their detection as nonthermal filament (NTF) candidates; for larger scales, see also Yusef-Zadeh et al. (2005) and Morris et al. (2017). Because the Brγ feature we investigate here is presumably influenced by the UV radiation of hot massive young He-stars (Yusef-Zadeh et al. 1996; Carlsten & Hartigan 2018; Kim et al. 2018) at the center of the GC stellar cluster, potentially including the S-stars, this gas can very likely be considered a thermal filament (TF) dominated by Bremsstrahlung emission (see Section 4.4). However, the morphology of NTF candidates is shaped by the magnetic fields of the GC. These magnetic fields imply a nonpoloidal shape, which also results in a complex structure. In order to differentiate between the TF and NTF character of the filaments, polarization measurements of the features at high angular resolutions are needed.

As shown in Section 3.4, the proper motion of the upper part of the Brγ Bar is around 320 km s\(^{-1}\) and therefore comparable with the proper motion of other filaments detected in the infrared in the vicinity of Sgr A*. For example, following the nomenclature of Mužić et al. (2007), NE3, NE4, and SW7 are showing proper motions that are in the same range.

4.3. Location of the Brγ-bar Features

While the Brγ-bar features we describe here are located close to the line of sight toward Sgr A*, one can raise the question of what is their true physical distance from the SMBH and the S-star cluster. Very close proximity to Sgr A* on scales of the S-cluster members would imply high orbital velocities of several hundred to a few thousand km s\(^{-1}\). Furthermore, the gaseous features would likely be distorted rather than almost linear. Hence, it is unlikely that they are in the immediate vicinity of Sgr A*. However, they could be part of the general minispiral flow. It seems peculiar that they are located in projection north of Sgr A*, rather than south where the bulk of the material is passing by Sgr A*. However, ALMA observations show that in the central few arcseconds and just north of the Sgr A* complex, extended emission can be found in the emission of density tracers like CS and H\(_2\)CO\(^+\) (Mosér et al. 2017). In fact, cinematic modeling of the gaseous minispiral material indicates that the gas is rather turbulent.

Vollmer & Duschl (1999) present a self-consistent hydrodynamic model of the gas flow in the minispiral system. They model the minispiral gas streams as three disk systems that are interleaved and form structures like the northern arm and the minispiral bar feature. In their modeling, the authors relate to the observations of the Sgr A West complex in the H92 line at 8.3 GHz with a resolution of 1" as presented by Roberts & Goss (1993) as well as the [Ne II](λ 12.8 μm) line emission observations described in detail by Lacy et al. (1991). Similar models of the minispiral gas have also been put forward by, e.g., Zhao et al. (2009) and Tsuboi et al. (2017).

In order to match the observations, Vollmer & Duschl (1999) allow for an ad hoc radial accretion velocity of 5% of the local Keplerian azimuthal velocity. They also find that a satisfactory description of the data is only possible if they allow for a disk-like flow with a turbulent velocity of 40% of the Keplerian velocity and a vertical turbulent velocity of 5% of the Keplerian velocity. The turbulent velocities determine the thickness and viscosity of the disk.

The authors point out that, in the framework of the standard theory of accretion disks (see, e.g., Frank et al. 1992), this corresponds to a viscosity parameter \( \alpha \sim 0.3 \). This is a value which is well within the range found for other types of disks. In Figure 17 of Vollmer & Duschl (1999), the authors plot the modeled disk material at low intensity levels and find that a tenuous gas component may fill almost the entire planes that represent gaseous stream of the northern arm and the bar.

Therefore, it seems conceivable that the Brγ-bar features we report are part of the turbulent minispiral as a stream that passes by Sgr A* from behind (see geometry of the model presented by Vollmer & Duschl 1999). This is consistent with the fact that no strong temporal variations in extinction, i.e., reddening, toward the S-cluster members or even the infrared counterpart of Sgr A* have been reported.
4.4. Stellar Wind–induced Ionization

Based on the detection of the bar through the SINFONI data, the emission of the ionized feature in the vicinity of Sgr A* is the focal point of several phenomena in the GC. The case B recombination lines imply UV radiation by the surrounding stars (Najarro et al. 1994, 1997; Martins et al. 2007). The authors of Karas et al. (2019) model the combination of a wind originating in a stellar cluster and the ISM, and they describe two shocks: a stellar wind shock and a jet shock induced by the ISM. The transition zone between the wind shock and the jet shock, which harbors clumps, is discussed in the following subsection. Calderón et al. (2016, 2020a) modeled and discussed the influence of the stellar winds of the Stars in the GC on scales of a few parsecs. Ressler et al. (2018) show even closer simulations of the inner parsec. The massive and luminous He-stars are the major wind sources. The lower luminous S-cluster stars may contribute to the wind impact onto the filaments only in the case where the Brγ filaments we describe here are close to the central arcsecond. The authors note that the S-star S2 and complex structures in the accretion wind have an influence on the low accretion rate that they derive to be a few $10^{-8} M_\odot$ yr$^{-1}$.

4.5. Shock-induced Clumpiness

As shown in Figure 1, the spectrum of the Brγ Bar shows a prominent [Fe II] and H2 line. Both emissions are indicators for shocks induced by stellar winds of young OB stars or an accretion wind onto and from Sgr A*. As already mentioned in Section 3.1, the H2S(0) line seems to be connected to a different object because of the large blueshifted line-of-sight velocity (see discussion in Section 4.6).

However, the [Fe II] emission can be associated with fast collisions of winds and gas clouds; as a consequence, shocks could be the reason for the ionization of the gas (Mouri et al. 2000). These shocks could then also be responsible for the observed and detected clumps as already simulated and discussed by Calderón et al. (2016). Our estimated lower mass limit of $2.5 \times 10^{-5} M_\odot$ is consistent with the mass that the authors derive for the clumps that are created by the collision of stellar winds produced by the S-stars.

4.6. The Blueshifted H2S(0) Line

We find that the L0 Brγ-bar feature is located at the position of the gap seen in the ALMA detection of a rotating disk structure (Murchikova et al. 2019). The authors report that the gap separates the red- and blueshifted parts of the disk spectrum. Within the uncertainties and the width of the rotating ALMA disk spectrum, our Brγ-bar feature L0 may be responsible for an absorption resulting in the detected gap (see corresponding comment in Murchikova et al. (2019)). This would make the bar feature a foreground object with respect to the structure detected with ALMA. Alternatively, the Brγ-bar L0 could be located at the center of the rotating ALMA disk, absorbing only the background disk emission. If the disk is orbiting Sgr A*, this would position the bar feature close to the center. This, however, would imply a high velocity spread (several 100 km s$^{-1}$, similar to the S-star cluster members) of the gas constituting the bar feature. That is not observed, and hence this explanation is more challenging and less likely.

4.7. Upcoming MIRI Observations

Considering the mid-infrared detection of features close to Sgr A*, the upcoming MIRI instrument on board the James Webb Space Telescope (JWST; Bouchet et al. 2015; Ressler et al. 2015; Ricke et al. 2015) offers a reasonable opportunity for observations. Even though the plate scale of MIRI is slightly increased compared to SINFONI, the size of the observed features ensures a continuum detection with MIRI. This is even more true considering the comparable plate scale of VISIR and NIRSpec and the detection of the Brγ Bar in the MIR (see Figure 4). With NIRSpec, we will have also access to a confusion-free Doppler-shifted Paα emission line thanks to the absence of telluric absorption and emission features. We are expecting a more complete picture of the observed structures. With the spectroscopic capabilities of MIRI, we will have broadband information about several emission lines like, e.g., CO, SiO, and CH$_3$ (Peißker et al. 2020b). The stable PSF of the JWST will also help to image faint and extended features in the central stellar cluster.

5. Conclusions

In this work, we have shown that the Brγ Bar located to the west of Sgr A* is in projection close to the S-cluster and exhibits a proper motion of around 320 km s$^{-1}$ in the westward direction. This velocity matches proper motion values of other infrared and radio features traced in that region (Yusef-Zadeh et al. 2004, 2017a; Mužić et al. 2007). Although it is close to Sgr A* in the line of sight, we argue that it is at least part of the minispiral passing by the very center. We find substructures that indicate a clumpiness that are most plausibly caused by the shocks of stellar winds. The lower limit for the mass of the observed Brγ-bar feature in the SINFONI FOV is $2.5 \times 10^{-5} M_\odot$. This value is in agreement with models of stellar wind interactions in the direct vicinity of Sgr A*. For this, we assumed a stellar wind velocity of 750 km s$^{-1}$. We find several indications that the observed Brγ feature is influenced by wind and shock interactions with the ISM west of Sgr A*. Based on the presented analysis, we suggest that the feature shows infrared line emission associated with a radio Bremsstrahlung filament. We can conclude that we need more data covering the area north and west of Sgr A* in order to investigate the full size of the feature in the NIR or additional gas reservoirs. Because we also observe another prominent Brγ-bar L1 west of Sgr A* (prominent in the MIR continuum emission), we are confident that observations with the JWST and future instruments like ERIS at the VLT will produce a more complete picture of the line emission features and filaments in the vicinity of Sgr A*. It is possible that the gas reservoir associated with the extended feature can be connected to the dusty objects also present in this region. They could be indicators of ongoing star formation in the central region of the stellar cluster harboring Sgr A*. Long-term observations could complete this speculative connection.

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Appendix A
Proper Motion Measurements and Individual Blobs

As described in Section 3.4, we use different methods in order to derive a proper motion based on the prominent upper part. With these methods, we derive a proper motion of around 320 km s\(^{-1}\). This velocity is in line with other known features. Mučić et al. (2007), for example, investigate thin dust filaments in the vicinity of Sgr A\(^*\) and derive typical proper motions of several hundred km s\(^{-1}\) (see also Yusef-Zadeh et al. 1998; Zhao & Goss 1998). Figure A1 shows indications that the B2V star S-star S2 blocks part of the Br\(^\gamma\) Bar (see also Figure 1). This can be noticed just above Sgr A\(^*\) in 2006. In 2018, when the star S2 is close to Sgr A\(^*\), the emission of the Br\(^\gamma\) Bar in the blocked areas from 2006 can be observed.

It should be noted that we see variable structures in the Br\(^\gamma\) line maps of the bar throughout the SINFONI data between 2006 and 2018 (Figure A1). The less prominent lower part of the bar shows an increased intensity in 2018 compared to 2006. Considering the observation in 2015, the results indicate a stream of gas from north to south, in contrast to the proper motion of the upper prominent part. This is supported by the lack of a bridge between the upper and lower part in 2006–2010 (see Figure A1). At the position of the gap, we detect Br\(^\gamma\) emission in 2013–2018.

Figure A1. Central few arcseconds of the Galactic center in 2006, 2015, and 2018. Proper motion vector for the prominent upper part is pointing toward the west with a proper motion of around 320 km s\(^{-1}\). Southern part of the bar is moving toward the southeast with a proper motion velocity of about 314 km s\(^{-1}\). Magenta contour lines correspond to the 2018 line map; green ones are based on the 2006 emission, to demonstrate the evolution of the bar (45% and 60% of the related peak emission).
Appendix B
Doppler-shifted Line Maps of the Brγ-bar L0

Here, we show a line map overview (see Figure B1). These channel maps are related to the emission lines discussed in Section 3.1.

Figure B1. Line maps of the Brγ-bar L0. Upper left panel shows a K-band image of the GC based on the co-added data (see Figure 1). For comparison, we add a 50% contour line (sky-blue) to the channel maps.

Appendix C
Data

In this section, we list the used SINFONI data between 2005 and 2018 (see Tables C1–C4). We distinguish between medium and high quality that is measured by applying a Gaussian to the PSF of S2. Values for the FWHM in the x and y directions that are higher than 7 px are considered medium, while those lower than 6.5 px are considered high. Because of a high airmass, bad seeing conditions, or an insufficient AO correction, fitting a Gaussian to S2 is not always possible. We also exclude data that do not follow the object-sky-object pattern because the sky variability in the NIR shows a detectable impact on the data (Davies 2007).

| Date          | Observation ID | Amount of on Source | Exp. Time |
|---------------|----------------|---------------------|-----------|
| YYYY:MM:DD   |                | Exposures          | (s)       |
|               |                | Total | Medium | High |
| 2005 Jun 16   | 075.B-0547(B)  | 20    | 12     | 8    | 300 |
| 2005 Jun 18   | 075.B-0547(B)  | 21    | 2      | 19   | 60  |
| 2006 Mar 17   | 076.B-0259(B)  | 5     | 0      | 3    | 600 |
| 2006 Mar 20   | 076.B-0259(B)  | 1     | 1      | 0    | 600 |
| 2006 Mar 21   | 076.B-0259(B)  | 2     | 2      | 0    | 600 |
| 2006 Apr 22   | 077.B-0503(B)  | 1     | 0      | 0    | 600 |
| 2006 Aug 17   | 077.B-0503(C)  | 1     | 0      | 1    | 600 |
### Table C1 (Continued)

| Date         | Observation ID | Amount of on Source Exposures | Exp. Time |
|--------------|---------------|-------------------------------|-----------|
| (YYYY: MM:DD)|               | Total | Medium | High |       |
| 2006 Sep 15  | 077.B-0503(C) | 5     | 0      | 5    | 600   |
| 2007 Mar 26  | 078.B-0520(A) | 8     | 1      | 2    | 600   |
| 2007 Apr 23  | 179.B-0261(F) | 7     | 2      | 1    | 600   |
| 2007 Jul 22  | 179.B-0261(F) | 3     | 0      | 2    | 600   |
| 2007 Jul 24  | 179.B-0261(Z) | 7     | 0      | 7    | 600   |
| 2011 May 2   | 087.B-0081(A)| 8     | 1      | 7    | 600   |
| 2011 Jul 27  | 087.B-0081(A)| 11    | 1      | 5    | 600   |
| 2012 Mar 18  | 288.B-5040   | 8     | 0      | 0    | 600   |
| 2012 May 5   | 081.B-0568(A)| 16    | 0      | 15   | 600   |
| 2012 Apr 7   | 081.B-0568(A)| 4     | 0      | 4    | 600   |
| 2012 May 21  | 183.B-0100(B)| 7     | 0      | 7    | 600   |
| 2013 May 23  | 183.B-0100(B)| 2     | 0      | 2    | 400   |
| 2013 May 24  | 183.B-0100(B)| 3     | 0      | 3    | 600   |

**Note.** The total amount of data is listed.

### Table C2

| Date         | Observation ID | Amount of On-source Exposures | Exp. Time |
|--------------|---------------|-------------------------------|-----------|
| (YYYY: MM:DD)|               | Total | Medium | High |       |
| 2013 Aug 28  | 091.B-0183(H)| 11    | 2      | 4    | 400   |
| 2014 Apr 2   | 093.B-0932(A)| 18    | 1      | 7    | 400   |
| 2015 Apr 14  | 093.B-0932(B)| 21    | 1      | 20   | 400   |
| 2015 Aug 16  | 095.B-0036(C)| 23    | 7      | 8    | 400   |
| 2016 Aug 20  | 097.B-0505(A)| 13    | 1      | 5    | 400   |
| 2017 Aug 25  | 099.B-0505(B)| 5     | 0      | 0    | 600   |
| 2018 Feb 17  | 101.B-0195(C)| 8     | 0      | 0    | 600   |

### Table C3

| Date         | Observation ID | Amount of On-source Exposures | Exp. Time |
|--------------|---------------|-------------------------------|-----------|
| (YYYY: MM:DD)|               | Total | Medium | High |       |
| 2015 Apr 8   | 093.B-0932(A)| 18    | 1      | 7    | 400   |
| 2015 Aug 17  | 095.B-0036(C)| 23    | 7      | 8    | 400   |
| 2016 Aug 20  | 097.B-0505(A)| 13    | 1      | 5    | 400   |
| 2017 Aug 25  | 099.B-0505(B)| 5     | 0      | 0    | 600   |
| 2018 Feb 17  | 101.B-0195(C)| 8     | 0      | 0    | 600   |

### Table C4

| Date         | Observation ID | Amount of On-source Exposures | Exp. Time |
|--------------|---------------|-------------------------------|-----------|
| (YYYY: MM:DD)|               | Total | Medium | High |       |
| 2017 Aug 25  | 099.B-0505(B)| 5     | 0      | 0    | 600   |
| 2018 Feb 17  | 101.B-0195(C)| 8     | 0      | 0    | 600   |

**Note.** The total amount of data is listed.
Table C4 (Continued)

| Date         | Observation ID | Amount of On-source Exposures | Exp. Time |
|--------------|----------------|-------------------------------|-----------|
| (YY:MM:DD)   |                | Total | Medium | High | (s) |
| 2018 May 20  | 0101.B-0195(D) | 8     | 0      | 4    | 600 |
| 2018 May 28  | 0101.B-0195(E) | 8     | 3      | 1    | 600 |
| 2018 May 28  | 598.B-0043(F)  | 4     | 0      | 4    | 600 |
| 2018 May 30  | 598.B-0043(F)  | 8     | 5      | 3    | 600 |
| 2018 Jun 3   | 598.B-0043(F)  | 8     | 0      | 8    | 600 |
| 2018 Jun 7   | 598.B-0043(F)  | 14    | 1      | 7    | 600 |
| 2018 Jun 14  | 0101.B-0195(F) | 4     | 0      | 0    | 600 |
| 2018 Jun 23  | 0101.B-0195(F) | 8     | 1      | 1    | 600 |
| 2018 Jun 23  | 598.B-0043(G)  | 7     | 2      | 1    | 600 |
| 2018 Jun 25  | 598.B-0043(G)  | 22    | 5      | 7    | 600 |
| 2018 Jul 2   | 598.B-0043(G)  | 3     | 0      | 0    | 600 |
| 2018 Jul 3   | 598.B-0043(G)  | 22    | 12     | 10   | 600 |
| 2018 Jul 9   | 0101.B-0195(G) | 8     | 3      | 1    | 600 |
| 2018 Jul 24  | 598.B-0043(H)  | 3     | 0      | 0    | 600 |
| 2018 Jul 28  | 598.B-0043(H)  | 8     | 0      | 3    | 600 |
| 2018 Aug 3   | 598.B-0043(H)  | 8     | 0      | 1    | 600 |
| 2018 Aug 6   | 598.B-0043(H)  | 8     | 1      | 1    | 600 |
| 2018 Aug 19  | 598.B-0043(I)  | 12    | 2      | 10   | 600 |
| 2018 Aug 20  | 598.B-0043(I)  | 12    | 0      | 12   | 600 |
| 2018 Sep 3   | 598.B-0043(J)  | 1     | 0      | 0    | 600 |
| 2018 Sep 27  | 598.B-0043(J)  | 10    | 0      | 0    | 600 |
| 2018 Sep 28  | 598.B-0043(J)  | 10    | 0      | 0    | 600 |
| 2018 Sep 29  | 598.B-0043(J)  | 8     | 0      | 0    | 600 |
| 2018 Oct 16  | 2102.B-5003(A) | 3     | 0      | 0    | 0   |

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