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Implication of Spin Constraints by the Event Horizon Telescope on Stellar Orbits in the Galactic Center

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Abstract

The center of the Milky Way hosts the closest supermassive black hole, Sgr A*. Decades of near-infrared observations of our Galactic Center have shown the presence of a small population of stars (the so-called S-star cluster) orbiting Sgr A*, which were recently reported to be arranged into two orthogonal disks. In this case, the timescale for the Lense–Thirring precession of S stars should be longer than their age, implying a low spin for Sgr A*. In contrast, the recent results by the Event Horizon Telescope favor a highly spinning Sgr A*, which seems to suggest that the S stars could not be arranged in disks. Alternatively, the spin of Sgr A* must be small, suggesting that the models for its observed image are incomplete.

Unified Astronomy Thesaurus concepts: Black holes (162); Kerr black holes (886); Galactic center (565)

1. Introduction

Supermassive black holes (SMBHs) are ubiquitous at the center of nearly every galaxy (Kormendy & Ho 2013). Sgr A*, at the center of our Milky Way, is the closest example, representing a unique laboratory to study stellar dynamics and to test general relativity under extreme conditions (e.g., Alexander 2017).

Sgr A* is surrounded by a kaleidoscopic environment, comprising young and old stars, compact remnants, gas, and molecular clouds (e.g., Genzel et al. 2010). Within ∼1 pc from the center of the galaxy, the dynamics of this multitude of astrophysical objects are dictated to leading order by the gravitational potential of the SMBH (e.g., Merritt 2013; Alexander 2017). Decades of near-infrared observations of our Galactic Center have shown that a population of about 40 stars (S2 has the shortest orbital period of about 15 yr), the so-called S-star cluster, orbits Sgr A* close enough that it can be used as a dynamical probe of its existence (e.g., Schödel et al. 2002; Ghez et al. 2003, 2008; Gillessen et al. 2009, 2017). These observations have constrained the mass of our SMBH to about $4 \times 10^6 M_\odot$, and have tested general relativity (e.g., Do et al. 2019; Gravity Collaboration et al. 2020). However, the spin of Sgr A* remains poorly constrained.

The Event Horizon Telescope (EHT) has made it possible to study SMBHs with direct imaging (Event Horizon Telescope Collaboration et al. 2019a). The mass and spin of SMBHs can be constrained by modeling interferometric EHT data sets with snapshot images of numerical simulations or semianalytic models (e.g., Agol & Krolik 2000; Broderick & Loeb 2005, 2006, 2009; Dexter et al. 2010). The first direct image of the SMBH at the center of M87 has shown the power of this unprecedented tool (Event Horizon Telescope Collaboration et al. 2019b).

Recently, the EHT collaboration released the first image of Sgr A*, which showed a compact emission region with intrahour variability (Event Horizon Telescope Collaboration et al. 2022a). Using a large suite of numerical simulations, the image of Sgr A* was shown to be consistent with the expected appearance of a Kerr black hole with a mass of about $4 \times 10^6 M_\odot$ (Event Horizon Telescope Collaboration et al. 2022b), in agreement with the current constraints from individual S-star orbits (e.g., Ghez et al. 2008; Gillessen et al. 2009). Moreover, the EHT models disfavor scenarios where the SMBH is viewed at a high inclination, with a preference for an inclination of about 30°, as well as disfavor a nonspinning black hole, with a preference for a spin $\chi_{\rm BH} > 0.5$ (see Figure 4 in Event Horizon Telescope Collaboration et al. 2022a).

The preference for rapidly rotating configurations has important implications for the stellar orbits of the stars around it. By analyzing the kinematics of the S stars, Ali et al. (2020) recently argued that they are arranged into two almost-orthogonal disks. Fragione & Loeb (2020) have shown that the spin of Sgr A* is then constrained to be $\chi_{\rm BH} \lesssim 0.1$ by requiring that the frame-dragging precession has not had enough time to drive the S stars out from their disky configuration.

In this Letter, we reanalyze the geometrical argument of Fragione & Loeb (2020) in light of the recent results from the EHT, and we discuss the implications of a possibly highly spinning Sgr A* for the distribution of the stellar orbits around it.

2. The Closest Stars to Sgr A*

Ali et al. (2020) recently argued that the S stars are arranged into two orthogonal disks (the so-called "red" and "black" disks), which are located at a position angle of approximately ±45° with respect to the Galactic plane. Peißker et al. (2020a, 2020b) also argued for the discovery of six new S stars, fainter and less massive than the classical S stars, some of which (in particular S62 on a 9.9 yr orbit) are even closer to Sgr

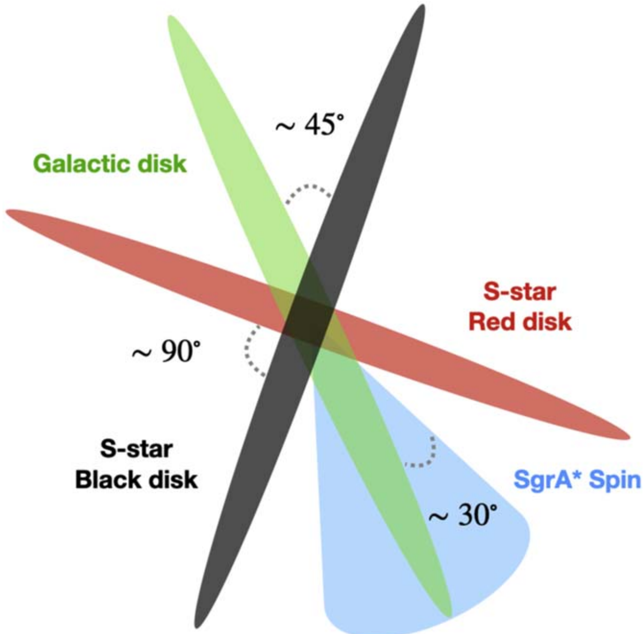

Figure 1. Schematic representation of the spatial configuration of the S stars, the Galactic disk, and the spin of Sgr A*. The red and black disks of S stars are roughly perpendicular to each other and inclined at about 45° with respect to the Galactic disk (Ali et al. 2020). The blue cone with an opening angle of about 30° represents the most likely orientation of the spin of Sgr A* (Event Horizon Telescope Collaboration et al. 2022b).

A* than S2. While the classical S stars have masses in the range of 8–14 $M_\odot$ (Habibi et al. 2017), Peißker et al. (2020b) estimated a mass of about 6.1 $M_\odot$ for S62 and a mass in the range of 2–3 $M_\odot$ for the other five new candidates.

The advent of the near-infrared GRAVITY instrument at the VLTI has marked the beginning of a new era in observations of the Galactic Center (Gravity Collaboration 2018a, 2018b). GRAVITY can improve the localization of the innermost stars in our galaxy by a factor of about 20 compared to adaptive optics and, most importantly, the high angular resolution of GRAVITY allows it to overcome the confusion limit of adaptive optics imaging. In a recent analysis of deep images of the Galactic Center, however, none of the GRAVITY sources matches the 9.9 yr orbital period star as reported by Peißker et al. (2020a). Moreover, using GRAVITY data, von Fellenberg et al. (2022) could not confirm that S stars in the central region are organized into two orthogonal disks.

Figure 1 illustrates the geometrical configuration of the red and black disks of S stars, respectively, according to the analysis of Ali et al. (2020). The two disks are nearly perpendicular to each other and inclined at about 45° with respect to the Galactic disk. The blue cone with an opening angle of about 30° represents the most likely orientation of the spin of Sgr A* according to the EHT analysis (see Figure 4 in Event Horizon Telescope Collaboration et al. 2022a).

3. Implications for the Spatial Distribution of S Stars

The spin angular momentum $\boldsymbol{S}$ of an SMBH of mass $M_{\rm BH}$ can be expressed in terms of the dimensionless spin $\chi_{\rm BH} = |\boldsymbol{S}|(GM_{\rm BH}^2/c)^{-1}$, where G is the gravitational constant and c is the speed of light. If the pericenter of the stars is close enough to the SMBH, its spin induces a Lense–Thirring (frame-dragging) precession, which simultaneously affects the

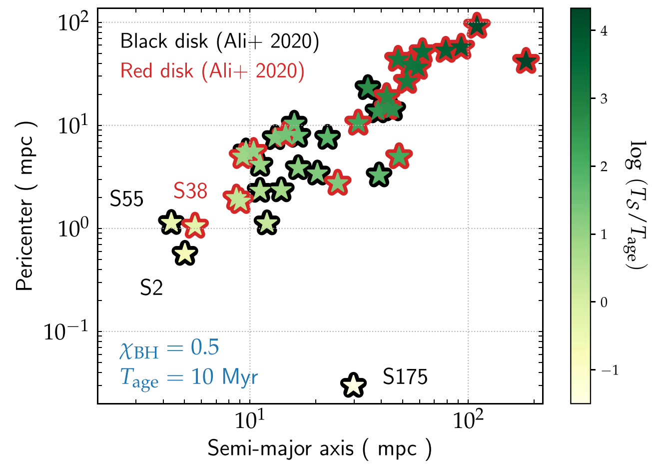

Figure 2. Orbital distributions of S stars according to Ali et al. (2020). The red and black symbols show the S stars in the red and black disks, respectively. The color code represents the ratio between the frame-dragging timescale (Equation (1)), assuming the spin of Sgr A* is $\chi_{\rm BH} = 0.5$ (Event Horizon Telescope Collaboration et al. 2022a), and the age of S stars, assumed to be 10 Myr (Habibi et al. 2017).

orbital inclination, the argument of periapsis, and the longitude of the ascending nodes (Lense & Thirring 1918). These three Keplerian orbital elements change over a characteristic timescale (e.g., Merritt 2013)

$$T_S = \frac{1}{\nu_S} = \frac{c^3 a^3 (1 - e^2)^{3/2}}{2\chi_{\rm BH} G^2 M_{\rm BH}^2}, \tag{1}$$

where a and e are the orbital semimajor axis and eccentricity of the star, respectively. According to Equation (1), the inclination of any stellar orbit within the SMBH equatorial plane would not be affected by frame dragging, while its effect would be maximal for stars with orbits orthogonal to the SMBH spin.

The frame-dragging precession by Sgr A* could have a nonnegligible effect on timescales that are shorter than the main-sequence lifetimes of massive stars on stellar orbits within a milliparsec of the Galactic Center (Levin & Beloborodov 2003). Only a handful of the known S stars have pericenter passages from Sgr A* small enough to be possibly affected by Lense–Thirring precession, assuming a nonzero spin of the SMBH. If the S stars are arranged into two orthogonal disks as argued by Ali et al. (2020), the timescale for frame-dragging precession of any star in the disks should be much longer than their age. Otherwise, the Lense–Thirring precession would have enough time to rearrange the orbital inclinations of the S stars, possibly erasing any disky signature.

Using the previous argument and assuming that the S stars formed in the same plane in which we find them today, Fragione & Loeb (2020) showed that the spin of Sgr A* can be constrained to be $\chi_{\rm BH} \lesssim 0.1$ if the classical S stars (that is, excluding the six new S stars claimed by Peißker et al. 2020a, 2020b) are indeed organized into two orthogonal disks. However, the recent results of the EHT collaboration show a preference for $\chi_{\rm BH} > 0.5$. Note that, because the SMBH is within about 30° from the line of sight (see Figure 1), this would imply that the frame-dragging precession would be nearly maximal for one of the two disks of S stars.

Figure 2 shows the timescale for frame dragging (Equation (1)) for the classical S stars in the two orthogonal red and black disks according to the analysis of Ali et al.

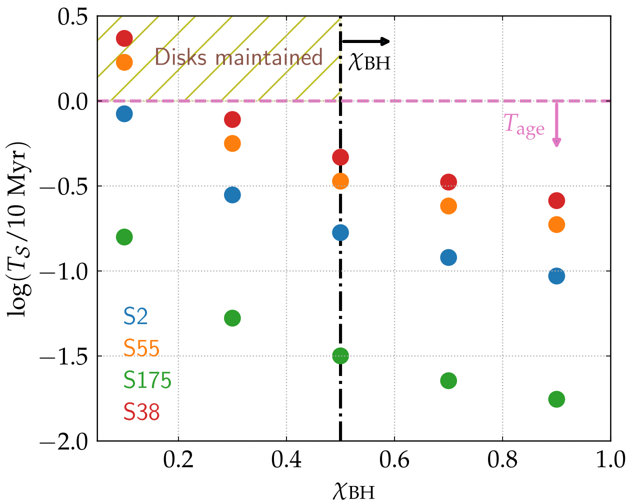

Figure 3. S stars (S2, S38, S55, and S175) with frame-dragging timescale shorter than their age as a function of the spin of Sgr A*. The black line represents the minimum spin of Sgr A* consistent with the EHT analysis (Event Horizon Telescope Collaboration et al. 2022a), while the pink line represents the upper limit on the ages of S stars from Habibi et al. (2017).

(2020). We assume that the spin of Sgr A* is $\chi_{\rm BH} = 0.5$ (Event Horizon Telescope Collaboration et al. 2022a) and that the age of S stars is 10 Myr (Habibi et al. 2017). Four of the S stars (S2, S38, S55, and S175) have a Lense–Thirring precession timescale shorter than their lifetime. This implies that the frame-dragging precession would have enough time to rearrange the orbital inclinations of these four S stars, driving them out of their current disks. Note that our argument holds whatever the relative inclination of the spin of Sgr A* is with respect to the red and black disks. While S2, S55, and S175 belong to the black disk, S38 lies on the red disk. Therefore, their relative orbital inclination with respect to the SMBH spin could be either about 15° or 75°, rendering the frame-dragging precession nearly maximal for at least one of these four S stars.

To show how our results depend on the spin of Sgr A* and the age of the S stars, we show the timescale for frame dragging (Equation (1)) for S2, S38, S55, and S175 as a function of $\chi_{\rm BH}$ n Figure 3. Only very small values of the SMBH spin ($\lesssim 0.1$) or very short stellar ages ($\lesssim 1$ Myr) would imply a precession timescale long enough to be consistent with these stars being organized into two orthogonal disks. Note that including the six newly claimed S stars by Peißker et al. (2020a, 2020b) would make the discrepancy between the SMBH spin favored by the EHT analysis and the one required by the orbits of S stars worse owing to the older stellar ages of these fainter and less massive stars.

4. Conclusions

Recently, the S stars orbiting around Sgr A* were claimed to be arranged into two orthogonal disks (Ali et al. 2020). In this case, the Lense–Thirring effect by the SMBH should not be strong enough to make their orbits precess and align them to the SMBH equatorial plane, thus requiring a negligible SMBH spin. However, the recent results by the EHT collaboration show a preference for the spin of Sgr A* to be $\chi_{\rm BH} > 0.5$.

We have reanalyzed the frame-dragging precession for the classical S stars and have shown that four of them (S2, S38, S55, and S175) have a Lense–Thirring timescale shorter than their lifetime. Only very small values of the SMBH spin ($\lesssim 0.1$) or very short stellar ages ($\lesssim 1$ Myr) would imply a precession timescale long enough to be consistent with these stars being in two orthogonal disks.

Our results may have two possible implications. Assuming the estimate of the spin of Sgr A* by the EHT collaboration holds, the S stars could not be organized into two orthogonal disks. This would be consistent with the fact that the disky signature observed by Ali et al. (2020) is stronger in projected coordinates rather than in physical ones and with the fact that the S stars seem to rotate in opposite directions in both disks, which is unlikely if the stars on the disks are coeval. Moreover, von Fellenberg et al. (2022) could not confirm that S stars in the central region are organized into two orthogonal disks using GRAVITY data. Also, there could be older S stars in a more isotropic distribution, which eluded detection owing to their lower luminosity. On the other hand, if the disky signature observed by Ali et al. (2020) holds, the spin of Sgr A* could not be too far from zero, in tension with the results of the EHT collaboration, which may suffer from uncertainties in the theoretical modeling of the emission by the accreting gas and the resulting black hole silhouette.

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