Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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A 4000 $M_\odot$ supermassive star as a possible source for the W1 kilomaser

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Abstract. Supermassive stars have been proposed as the solution to a number of longstanding problems in globular cluster formation. The hypothetical stars have been suggested as potential polluters responsible for the observed chemical peculiarities within those clusters. In recent hydrodynamic simulations, we have demonstrated that accretion discs around such stars are stable even with large stellar accretion and flyby rates and produce H_2O kilomasers. We propose that the W1 kilomaser, associated with a super star cluster in the starburst galaxy NGC 253, may arise in an accretion disc around a supermassive star with a mass of around 4000 $M_\odot$.

Keywords. star clusters, masers, accretion discs, hydrodynamics

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1. Globular clusters

Globular clusters are known as some of the oldest objects in the universe, with the oldest ones having an age of more than 13 Gyr. These ancient clusters exhibit unique chemical compositions, a characteristic that has puzzled astronomers for decades. Studies dating back to the 1960s revealed an interesting phenomenon known as the '2nd parameter problem', where globular clusters with the same metallicity display different horizontal branch morphologies in their colour-magnitude diagrams (Sandage & Wildey, 1967). Spectroscopic measurements conducted in the 2000s demonstrated that most Galactic and extra-galactic globular clusters exhibit multiple main sequences across the colour magnitude diagram (Anderson *et al.* 2002). This is considered to be a consequence of variations in helium abundance (Norris, 2004), providing evidence that globular clusters harbor multiple stellar populations (Bastian & Lardo, 2018). Globular clusters also display large variations in light elements, particularly Na-O, C-N and Mg-Al anticorrelations (Denissenkov *et al.* 1990), with the most prominent feature in most of them being the Na-O anticorrelation. A hot-hydrogen burning environment is needed to vary those abundances with the concurrent p-capturing reactions of the CNO-cycle ($\gtrsim$ 20 MK), NeNa ($\gtrsim$ 45 MK) and MgAl ($\gtrsim$ 70 MK) chains leading to the rise of those anticorrelations (Gratton *et al.* 2012; Prantzos *et al.* 2017). Most models, seeking to explain these anomalies in globular clusters invoke a process called self-enrichment, wherein certain stars within a cluster, known as polluters, enrich other stars within the same cluster.

2. Supermassive stars

Supermassive stars (SMS, >1000 $M_\odot$) are hypothetical stars, proposed as candidates for polluters responsible for the chemical peculiarities in those ancient clusters. These stars reach the essential central temperature required to activate the MgAl chain early in their evolution, when the abundance of helium is still low (Prantzos *et al.*

2017). During their early main sequence phase, the H-burning products of supermassive stars exhibit agreement with various observed anticorrelations in globular clusters (Denissenkov & Hartwick, 2014). It is assumed that supermassive stars are fully convective and release material through a radiatively driven wind at the beginning of their main sequence phase. The wind is quickly decelerated by interaction with dense gas in the embedded cluster. The ejecta would then mix with star-forming gas that either accretes on to protostars or collapses to form stars independently (Krause *et al.* 2020). The model proposed by Gieles *et al.* (2018), which suggests the concurrent formation of protoglobular clusters and supermassive stars, provides the correct chemical patterns through the "conveyor-belt" production of hot-H burning yields. This model also resolves the mass budget problem faced by other proposed polluter models, which typically require non-standard assumptions to produce the required mass of polluted gas. In this model, the supermassive star maintains its mass through accretion of protostars while losing mass via its wind. As a result, it cycles through a significantly larger amount of mass than its initial mass. However, a major drawback of this model is that no such objects have been observed to date (Renzini *et al.* 2022). The candidate forming massive clusters are located outside the Milky Way with very dense centers, where the hypothetical star would be obscured by gas and dust (Hollyhead *et al.* 2015). This makes direct observation challenging.

3. Kilomasers

An alternative method that could be used to detect those exotic objects is through kilomasers. 22.2 GHz water masers are commonly associated with massive star formation (Ellingsen *et al.* 2018). Krause *et al.* (2020) have suggested that the more luminous kilomasers could originate from the accretion disc around supermassive stars, similar to the even more luminous AGN megamasers. Recently, a very strong nuclear kilomaser, W1 (Fig. 1, right column, orange spectrum), has been found in a nearby galaxy (NGC 253) that is associated with a forming super star cluster (Gorski *et al.* 2019). Other kilomasers have also been observed in connection with intense star formation, e.g. in the Antennae galaxies (Darling *et al.* 2008), where spatial resolution has allowed for direct association with super star clusters (Brogan *et al.* 2010). W1 exhibits three distinct line systems: the prominent one at a systemic velocity of 116 km s^{-1} and two 'high velocity' features on either side of the systemic velocity at substantially lower flux. If a maser shows two or three of these corresponding lines (or line systems), it is referred to as a clean disc maser (Pesce *et al.* 2015), a characteristic typically observed in AGN megamasers. Although the spectrum of W1 resembles that of a disc maser, its luminosity is much weaker compared to typical AGN megamasers, being approximately two orders of magnitude lower. Some extragalactic kilomasers found in super star clusters have been compared to the Galactic high mass star forming region W49N, located roughly 11.1 kpc away (Gwinn *et al.* 1992). This region produces a large number of highly variable 22 GHz H_2O maser spots with the total luminosity of $\approx 1\ L_\odot$ (Zhang et al. 2013), making it also a kilomaser. The spectrum consists of 316 individual narrow lines (McGrath *et al.* 2004), but in all cases, the extragalactic kilomasers appear to have a more peaked and narrower spectrum. The spectrum of W1 is clearly different from the one of W49N.

4. Simulations and results

In a recent theoretical study (Nowak *et al.* 2022), we have verified with 2D hydrodynamic simulations that an accretion disc around a collisionally supported supermassive star would be able to survive and could produce collisionally pumped maser lines with fluxes and spectral shape similar to the high-velocity wings in W1 (we did not model

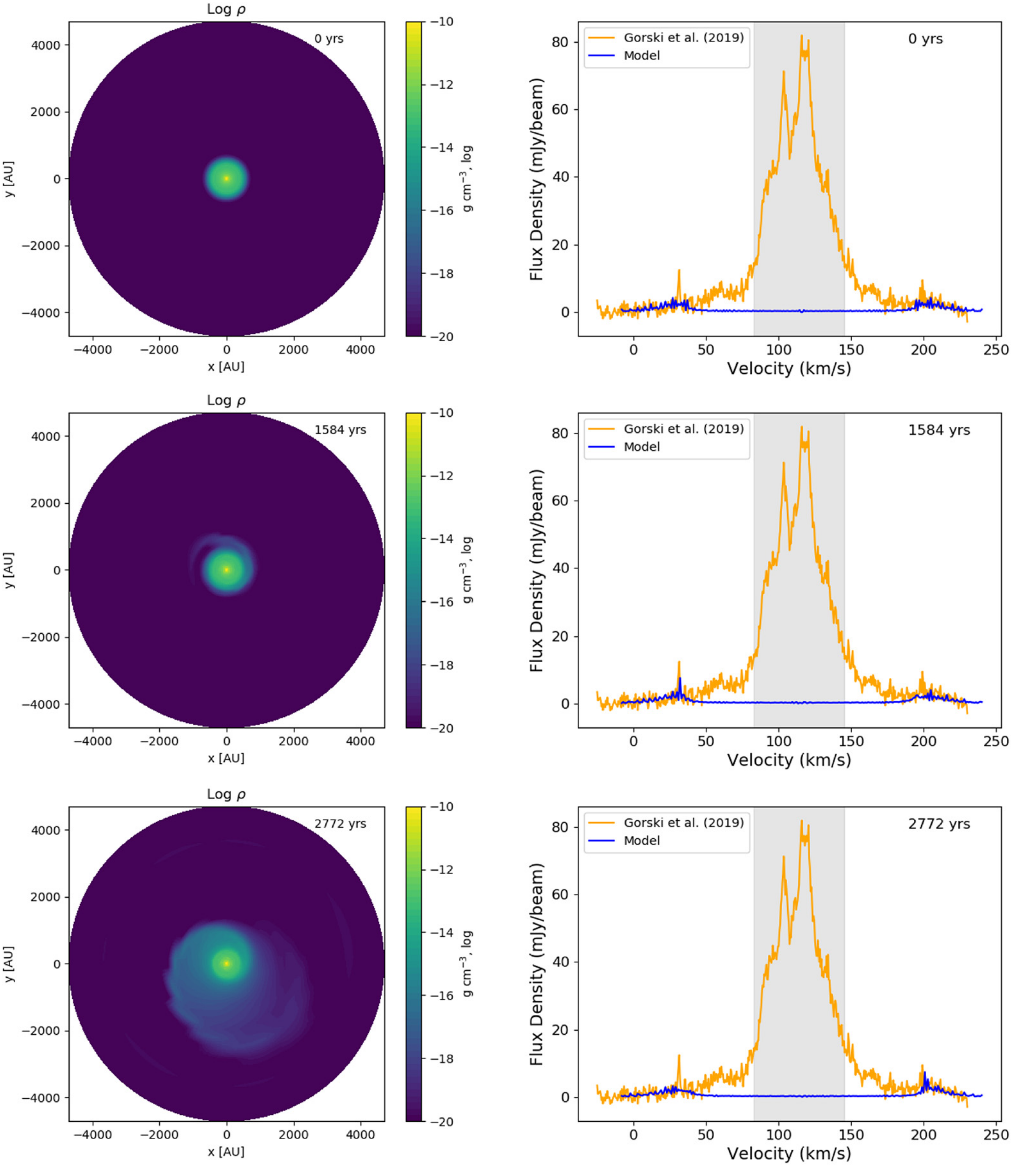

Figure 1. The time evolution of the reaction of an accretion disc around an SMS with a mass of 4000 $M_\odot$, a disc radius of 500 au, and a disc mass of 10 $M_\odot$, similar to Nowak *et al.* (2022), but using linear interpolation of perturbers' positions and improved modelling of long-range forces. The flyby rate considered in this hydrodynamics model is one stellar perturber per year. The density plots are presented in the left column, with the corresponding maser spectra on the right, for selected time steps. The model spectrum is shown in blue, whilst the W1 kilomaser from Gorski *et al.* (2019) for comparison is plotted in orange.

the radiatively pumped brighter central feature, indicated by shaded area, Fig. 1, right column, blue line). The maser spectrum, corresponding to a model with an SMS mass of 4000 $M_\odot$, exhibits high-velocity peaks that coincide with those observed in the W1 kilomaser. The density plots in Fig. 1 (left column), demonstrate the evolution of the disc as perturbers interact and create spiral arms within the disc. These perturbations in the disc structure have a significant impact on the peaks observed in the model maser, causing them to either move inward or outward, as well as increasing their flux. Based on our results, we propose that a supermassive star of this nature can provide an explanation for the observed W1 kilomaser.

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References

Anderson J., in van Leeuwen F., Hughes J. D., Piotto G., 2002, *ASP-CS*, Vol. 265
Bastian N., Lardo C., 2018, *ARAA*, 56, 83
Brogan C., Johnson K., Darling J., 2010, *ApJ*, 716, L51
Darling J., Brogan C., Johnson K., 2008, *ApJ*, 685, L39
Denissenkov P. A., Denisenkova S. N., 1990, *Soviet Astron.*, 16, 275
Denissenkov P. A., Hartwick F. D. A., 2014, *MNRAS*, 437, L21
Ellingsen S. P., Voronkov M. A., Breen S. L., Caswell J. L., Sobolev A. M., 2018, *MNRAS*, 480, 4851
Gieles M. *et al.* 2018, *MNRAS*, 478, 2461
Gorski M. D. *et al.* 2019, *MNRAS*, 483, 5434
Gratton R. G., Carretta E., Bragaglia A., 2012, *A&AR*, 20, 50
Gwinn C. R., Moran J. M., Reid M. J., 1992, *ApJ*, 393, 149
Hollyhead K. *et al.* 2015, *MNRAS*, 449, 1106
Krause M. *et al.* 2020, *Space Sci. Revs*, 216, 64
McGrath E. J., Goss W. M., De Pree C. G., 2004, *ApJS*, 155, 577
Norris J. E., 2004, *ApJ*, 612, L25
Nowak K., Krause M. G H., Schaerer D., 2022, *MNRAS*, 516, 5507
Pesce D. W. *et al.* 2015, *ApJ*, 810, 65
Prantzos N., Charbonnel C., Iliadis C., 2017, *A&A*, 608, A28
Renzini A., Marino A. F., Milone A. P., 2022, *MNRAS*, 513, 2111
Sandage, A., Wildey, R. 1967, *ApJ*, 150, 469
Zhang B., Reid M. J., Menten K. M., Zheng X. W., Brunthaler A., Dame T. M., Xu Y., 2013, *ApJ*, 775, 79