Thin filaments at the Galactic Center: identification and proper motions

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Abstract. L'-band (3.8 μm) images of the Galactic Center show a large number of thin filaments in the mini-spiral, located close to the mini-cavity, along the inner edge of the northern arm and in the vicinity of some stars. We interpret them as shock fronts formed by the interaction of a central wind with the mini-spiral or, in some cases, extended dusty stellar envelopes. The observations have been carried out using the NACO adaptive optics system at the ESO VLT, in 5 subsequent epochs from 2002 to 2006. We present a proper motion study of the thin filaments observed in the central parsec around Sgr A*, obtained using the cross-correlation technique. Our interpretation is consistent with a collimated outflow model from the central few arcseconds. Two possible mechanisms could produce the postulated outflow: stellar winds originating from the high-mass-losing He-star cluster as well as a wind from Sgr A* due to accretion from the surrounding disk of stars.

1. Introduction

The central cavity of the Galactic Center is surrounded by a dense clumpy molecular ring (also called circum nuclear disk, CND) of warm dust (Zylka et al. 1995) and neutral gas (Güsten et al. 1987; Jackson et al. 1993; Wright et al. 2001; Herrnstein & Ho 2002). The central cavity itself has much lower mean gas density and contains the so called mini-spiral, which consists of mostly ionized gas and dust, and connects the CND to the center of the stellar cluster. The three-dimensional shape of mini-spiral is studied in detail by Vollmer & Duschl (2000) and Paumard et al. (2004).

A cluster of massive stars resides in the central parsec of the Galaxy (Blum et al. 1995; Krabbe et al. 1995; Genzel et al. 1996, 2000; Eckart et al. 1999; Clénet et al. 2001; Paumard et al. 2006). Within that cluster the 7 most luminous (L>10⁵.75 L⊙ ), moderately hot (T<10⁴.5 K) blue super giants contribute half of the ionizing luminosity of the region (Najarro et al. 1997; Krabbe et al. 1995; Blum et al. 1995). These stars, mostly HeI emission line stars, undergo high mass loss through strong stellar winds, the total mass loss rate being ~10⁻³M⊙ yr⁻¹ (Najarro et al. 1997). There is strong evidence for the fact that most of the young and hot stars orbit the very center of the Milky Way in at least one disk like structure well within the central stellar cluster (Genzel et al. 2000, 2003; Levin & Beloborodov 2003; Beloborodov et al. 2006; Paumard et al. 2006).

Adaptive optics L'-band (3.8μm; Fig. 1) images of the central parsec of the Milky Way show large amounts of gas and dust that belong to the mini-spiral. Additionally, one can distinguish between a large number of thin filaments (some have already been reported by Clénet et al.
Figure 1. Left: L'-band image of the central part of the Milky Way ($\sim 17 \times 17$ arcsec$^2$). The image contains a large number of dust embedded stellar sources, and shows the emission from the mini-spiral and a number thin filaments that are associated with this emission. The boxes mark thin filaments with measurable proper motions. Right: High-pass filtered version of the image shown on the left. Here all compact features are enhanced. The cross in the left image marks the position of Sgr A*.

2004) Here, we identify them and present proper motion measurements. We argue that they are most likely shock fronts formed by the interaction between an outflow from the central arcseconds with the ambient ISM.

2. Observations and Data Reduction
The observations were performed using the NAOS/CONICA adaptive optics assisted imager/spectrometer (Lenzen et al. 1998; Rousset et al. 1998; Brandner et al. 2002) at the UT4 (Yepun) at the ESO VLT. The data set includes L'-band images from 5 epochs (2002.660, 2003.356, 2004.320, 2005.364 and 2006.408). Data reduction and formation of final mosaics were performed using the DPUSER software for astronomical image analysis (T. Ott; see also Eckart & Duhoux 1990). The images were transformed to a common coordinate system (that of the epoch 2003.356), using IDL image transformation routines. The transformation was performed to second order and provides correction of all translations, rotations and possible warps between two images.

In order to highlight the above mentioned filaments, we produced high-pass filtered maps (Fig. 1, right) by subtracting a smoothed version of the images from themselves and smoothing the final images. As a smoothing function we used a 4 pixel Gaussian (the images have a pixel scale of 27 mas/pixel and a resolution of $\sim$100 mas). This procedure enhances all structures that have significant power at spatial frequencies that correspond to the diffraction limited beam size.

3. Proper motions of the thin filaments
3.1. Identification and description of the thin filaments
Fig. 2 shows a schematic representation of the thin filaments observed in the central parsec of the Milky Way. The features located west and south from Sgr A* are denominated SW, those
associated with the northern arm and located east from Sgr A* NE, and the features most probably associated with stars are marked with X. The shocks labeled NE are located along the inner rim of the northern arm and are curved with their convex sides eastwards. Shocks to the west and southwest of Sgr A* are curved with their convex sides westward and are positioned almost perpendicular to the Bar. Exceptions are X3, X4 and X7. X4 is associated with IRS 3, whose bow-shock-like appearance leads to a picture in which the extended dust shell of the mass-losing star is being pushed northwest by a wind from the IRS 16 cluster or Sgr A* (Viehmann et al. 2005). Additionally, IRS 3 has a proper motion component to the southeast, approximately into the direction in which we observe the shock. X3 and X7 are located along the line to Sgr A* and could be due to the postulated central outflow (see below). Features X1, X5 and possibly X6 appear to be associated with individual stars and are probably formed by the interaction between a stellar wind, probably in combination with the stellar motion, and the interstellar medium. X1 is directly associated with a star, both moving in the same direction on the sky, with the comparable plane of the sky velocity. For X5 no significant proper motion was detected, but taking into account the significantly higher brightness of this feature with respect to the other filamentary structures, we suppose that there is an embedded or background star present that cannot be separated from the emission of the bow-shock. On the west side of the mini-cavity, at the location of the IRS13/IRS2 complex or just south of it, we can identify several luminous shocks that cannot be associated with stars in a straightforward way (SW5, SW6, SW7, SW8).

3.2. Results
In order to determine the relative offsets between the positions of the filaments in different epochs, the cross-correlation technique was used. All offsets were calculated with respect to the chosen reference epoch (2003.356). Uncertainties in the proper motions are due to the linear regression uncertainty as well as to the uncertainties of the image transformation and the cross-correlation routine. Table 1 summarizes the proper motions of thin filaments obtained in our study, assuming a distance to Sgr A* of 8 kpc. The velocities of all features, except that of X1 and SW7, are measured approximately perpendicularly to the feature of interest. This results in minimizing the error since many of the filaments are parts of more extended features that could not be completely extracted (e.g. because of the proximity to stellar sources), which basically means that the motion along the feature does not result in a measurable proper motion. Feature X1 is clearly a stellar bow shock, caused by motion of the star (offset from Sgr A* by 2.95″ in
Table 1. Proper motions of thin filaments

| Name | $\Delta \alpha$ (arcsec) | $\Delta \delta$ (arcsec) | size($\Delta x \times \Delta y)$ (arcsec $\times$ arcsec) | $v$ (km/s) | $\Delta v$ (km/s) |
|------|--------------------------|--------------------------|-----------------------------------------------|------------|------------------|
| NE1  | 4.76                     | 3.42                     | $0.32 \times 0.46$                            | -29        | 16               |
| NE3  | 2.62                     | -0.09                    | $0.38 \times 0.41$                            | 167        | 25               |
| NE4  | 0.32                     | -1.95                    | $0.43 \times 0.43$                            | 130        | 18               |
| SW3  | -6.08                    | -0.77                    | $0.35 \times 0.35$                            | -229       | 19               |
| SW5a | -4.20                    | -2.31                    | $0.35 \times 0.11$                            | -165       | 15               |
| SW5b | -4.13                    | -2.75                    | $0.16 \times 0.24$                            | -123       | 22               |
| SW7(R.A.) | -3.07                | -5.10                    | $0.73 \times 1.22$                            | -186       | 17               |
| SW7(Dec.) | -3.07                | -5.10                    | $0.73 \times 1.22$                            | -80        | 21               |
| X1(R.A.) | 3.22                     | 3.40                     | $0.30 \times 0.38$                            | 113        | 16               |
| X1(Dec) | 3.22                     | 3.40                     | $0.30 \times 0.38$                            | -78        | 21               |

Table 2. Positions in right ascension and declination are relative to Sgr A *refer to the center of the box used to extract the filament. All velocities in the table are measured in direction perpendicular to the shock feature except for X1 and SW7. The proper motions of X1 and SW7 are given in R.A. and Dec.

R.A. and 3.46′′ in Dec) into the medium of the mini-spiral. The proper motion of the bow shock calculated in this work is in very good agreement with the proper motion of the associated star.

3.3. Discussion

There is strong evidence for the existence of at least one stellar disk at the Galactic center. 11 He emission line stars are located within a plane of this (clockwise-rotating) disk, most of them within a radius of 0.1 pc (2.5 arcsec) from Sgr A* (Genzel et al. 2000, 2003; Levin & Beloborodov 2003, Paumard et al. 2006). Strong stellar winds from the He stars cause high mass-loss rate: in total they lose $\sim 10^{-3} M_\odot$ yr$^{-1}$ (Najarro et al. 1997). Estimates of the rate at which the material is accreted onto the SMBH at the position of Sgr A* vary depending on the model used (see e.g. Quataert 2003, Baganoff et al. 2003, Narayan et al. 1998, Blandford & Begelman 1999, Yuan et al. 2002), but it is important to note that all of them deal just with a small fraction (less than 1%) of the material available from the high mass-losing stars. This means that, independent of the exact processes that happen on the scale of the Bondi radius, most of the material supplied by the stars never gets close to the BH, i.e. it is blown from the center and therefore can interact with the material of the mini-spiral.

$H_2$(1-0) S(1) molecular hydrogen line emission from the CND is concentrated on the northern and southern lobes (Gatley et al. 1984, 1986; Burton & Allen 1992; Yusef-Zadeh et al. 2001). The extinction-corrected peak line intensity from the lobes is about a factor 4 higher than the mean surface brightness of the CND (Yusef-Zadeh et al. 2001). The source of excitation of the $H_2$ emission associated with the CND is unclear. Although the bright appearance of the lobes is usually interpreted as due to the limb brightening of the 0.5 pc thick CND torus, inclined $\sim 70^\circ$ to the line of sight (Jackson et al. 1993), the limited size of the lobes and their symmetrical position with respect to Sgr A* suggest that the $H_2$ line emission from the lobes could be dominated by the interaction with a collimated wind.

An alternative source of the outflow could be a jet-like structure directly associated with the black hole at the position of Sgr A*. Then the collimation would have to be seen as a consequence of the yet unexplained accretion process onto the black hole, but could still be linked to the plane the mass-losing He-stars are moving in. The motion within a single plane implies that the viscous friction of gas being blown into that plane is larger than that for gas being blown out...
perpendicularly to it. On the one hand that results in a pressure gradient perpendicular to the plane, on the other hand it will result in an accretion flow within that plane onto the central black hole and may give rise to a corresponding outflow perpendicular to it.

This scenario would explain the overall geometry shown in Fig.1 and would allow the northern and southern lobes within the CND to be associated with the outflow. Which of the two mechanisms is dominant or whether both mechanisms in combination with the deep central potential provided by the $3.6 \times 10^6 M_\odot$ black hole represent an efficient collimation process has to be investigated via detailed hydrodynamical model calculations.

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