MINI-SPIRAL AT THE GALACTIC CENTER: A LINK BETWEEN ITS STRUCTURE AND THE VALUE OF A CENTRAL POINT MASS

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The innermost 2 pc contain a rotating ring ("circumnuclear disk") of molecular gas, neutral hydrogen, and dust with an embedded H II region called Sgr A West; a dense stellar cluster; and a compact nonthermal radio source Sgr A* (for a recent review, see Blitz *et al.* 1993). The clumped, spiral-shaped morphology of Sgr A West, sometimes called "the mini-spiral", has been a subject of numerous speculations concerning its origin (for a review, see Genzel & Townes 1987). Lacy *et al.* (1991) demonstrated that both the kinematics and shape of a part of Sgr A West can be fairly well approximated using an one-armed density-wave model.

In this paper (and a related one by Fridman *et al.* 1994), we make a next step in this direction and consider the observed structure of the mini-spiral as a result of hydrodynamical instability of the gaseous disk rotating in the gravitational field of the stellar cluster with an embedded central point mass. Self-gravitation of the disk is negligible as its gravity is small compared to hydrodynamical forces (see Lacy *et al.* 1991).

The rotation curve of the disk outside $r \sim 1.5$ pc is fairly well approximated by $V_\varphi = \text{const} \sim 110$ km/s (Serabin *et al.* 1986; Güsten *et al.* 1987; Sutton *et al.* 1990). Closer to the center, in the region where the

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central point mass could dominate, it should go up into the Keplerian law $V_\varphi \propto r^{-1/2}$. Therefore, somewhere inside 1.5 pc a kink on the rotation curve should appear. In the work by Fridman *et al.* (1994), we have analytically shown that a kink of the rotation curve can lead to instability, which results in the generation of a spiral density wave. As it follows from our study, in the disk with a sharp kink the modes with a large number of spiral arms are the most unstable. In the disk with a smooth kink, as numerical simulations (Lyakhovich *et al.* 1994) have shown, the azimuthal number of the most unstable mode decreases with an increase in the kink width. For a very smooth kink, a mode with one spiral arm is only unstable.

The hydrodynamical model predicts that the generated density wave must have the shape of an Archimedes spiral outside R_{res}, the corotation radius. Observational data indicate that the morphology of the mini-spiral has, indeed, the shape of an Archimedes spiral outside 0.1-0.3 pc (Lacy *et al.* 1991). Therefore, the morphology of the mini-spiral could serve an argument in favor of the hydrodynamical origin of this structure.

The morphology of the mini-spiral can provide information about its corotation radius and pattern speed. Indeed, since the generated density wave must have the shape of an Archimedes spiral outside the corotation radius *only*, the minimal distance down to which the shape of the density wave is approximated by an Archimedes spiral can be used to evaluate the corotation radius. It follows from the shape of the mini-spiral that the corotation radius equals to 0.1-0.3 pc.

As shown by Fridman *et al.* (1994), a simple relationship exists between the pattern speed, Ω_{res}, and the pitch angle, i, of the spiral arm:

$$\Omega_{res} = -\frac{c}{r \tan i}, \tag{1}$$

where c is the "sound speed" (the chaotic velocity of the clouds) and r is the radial distance. Parameters c and i are given by observations outside the corotation region: for the mini-spiral $|r \tan i| = |dr/d\varphi| \gtrsim 0.1$ pc rad^{-1} in the region $r \sim 1$ pc (see Lacy *et al.* 1991) and for the disk $c \leq$ 30-50 km/s (Lacy *et al.* 1991, Roberts and Goss, 1993). ¿From this we obtain $\Omega_{res} \lesssim$ (300 - 500) km pc^{-1} (rad) s^{-1}.

The mini-spiral parameters, R_{res} and Ω_{res}, can be determined more accurately by comparison of the shape of the observed mini-spiral with that for the model spiral obtained by numerical simulations. Below, some results are given of numerical simulations for the mini-spiral generation in the gaseous disks with a smooth kink in the rotation curve.

In our numerical simulations, we used the code described in Fridman *et al.* (1994). The profile of the unperturbed rotational velocity with a kink was modelled by

$$\frac{V_\varphi(r)}{V_1} = \left(\frac{r}{R_0}\right)^{\frac{n_1+n_2}{2} - \frac{n_1-n_2}{\pi}\arctan\left[\frac{2(r-R_0)}{l}\right]+1}. \qquad (2)$$

Here R_0 is the radial distance to the kink in the rotation velocity, l is the characteristic width of the kink; V_1=110 km/s; n_1=-1.5 and n_2=-1 are to match the approximations $V_\varphi = \text{const} = V_1$ for $r \gg R_0$ and $V_\varphi \propto r^{-1/2}$ for $r \ll R_0$. The profile of the unperturbed surface density of the gaseous disks was, for simplicity, approximated by $\Sigma(r) = \text{const}$ (for the other cases, see Lyakhovich *et al.* 1994 and Fridman *et al.* 1994). The profile of the sound speed was taken to be $c(r) = \text{const}$, which is consistent with an isotermal model of the disk. The value of sound speed was taken in the range of 30 km/s $< c <$ 50 km/s. Numerical simulation showed that the maximum value of the kink smoothing, l, at which the mini-spiral is still generated for these parameters, is as large as $l = (0.3 - 0.4)\ R_0$. Thus the instability can take place even at a rather smooth rotation curve.

Fig. 1 shows the numerical model superimposed onto the observed contour map of the mini-spiral. Fig. 2 demonstrates the rotation curve used for the modelling of the spiral wave shown in Fig. 1. A visual inspection of Fig. 1 suggests that the model is able to describe the data fairly well.

By changing the sound speed in the range (30 - 50) km/s we obtain the values of other parameters of the disk for which our model fits the observed mini-spiral fairly well. While doing so one obtains the position angle of the disk 17°-25°, the inclination of the disk 59°-67°, and the position of the center of rotation 0″-2″ West and 0″-2″ South off Sgr A*. These results are consistent with the observational data (see Table 1).

In the frame of our model we determine the other parameters of the mini-spiral: Ω_{res} = (400-500) km pc^{-1} s^{-1} and $R_{res} = 0.2 - 0.3$ pc.

It follows from our analytical and numerical studies that the corotation radius and the radial distance of the kink are close to each other. Thus the rotation velocity is approximately constant outside r = 0.3 pc, which is also consistent with the data presented in Lacy *et al.* (1991).

The above parameters of the mini-spiral allow us to determine the total enclosed mass inside R_{res}. In the disk the pressure force can be neglected compared to the centrifugal one (since their ratio is $\sim c^2/V_\varphi^2 \lesssim 0.2 - 0.07$). The balance of the centrifugal force with the outer gravitating forces induced by both the stellar cluster and a central point mass yields

$$M(r) = \Omega^2(r) r^3/G, \qquad (3)$$

where G is the gravitational constant. Substituting the values of $r = R_{res}$ and $\Omega = \Omega_{res}$ we obtain the total enclosed mass inside the radius (0.2-0.3) pc to be $(3 - 7) \times 10^5$ $M_\odot$. Bearing in mind that the inferred core mass of

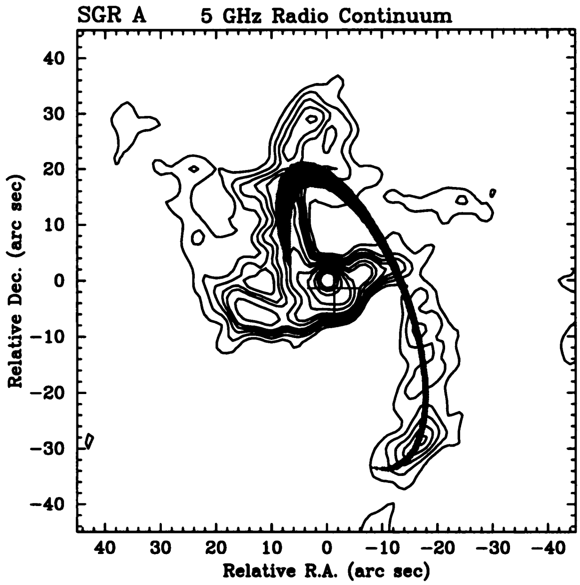

Figure 1. The mini-spiral: the contour map is the observational data (Blitz *et al.* 1993), the filled region is the computer simulation, the cross is the center of rotation. The offset for the rotational center with respect to Sgr A* is 0.″6W and 1.″3S [the rotational center coincides with the center of the stellar cluster, 0.″6W ± 0.″7, 1.″3S ± 1.″0 (3 σ errors), as given by Eckart *et al.* 1993]. The sound speed $c = 50$ km/s. The inclination of the disk is 60°, the position angle of the disk is 20°.

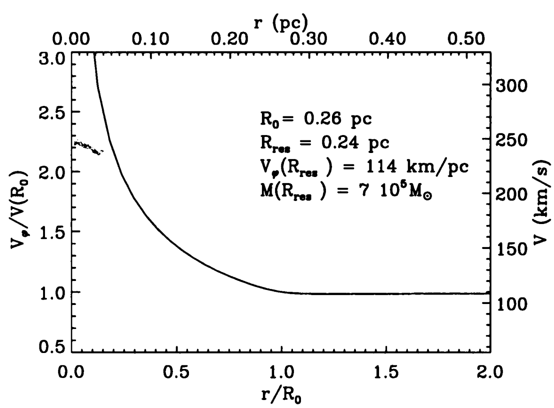

Figure 2. The rotation curve used for the modelling of the spiral wave shown in Fig. 1. The parameters of the curve (see Eq. 2) are $n_1 = -1.5$, $n_2 = -1$, $l/R_0 = 0.3$, and $V_1 =$ 110 km/s.

TABLE 1. The mini-spiral parameters

Model Parameter	1	2	3	4	5	6
Position angle	$21° \pm 4°$	$15° \pm 2°$	$22° \pm 5°$	$\approx 20°$	$\approx 12°$	$15° \pm 15°$
Inclination	$63° \pm 4°$	$65° \pm 5°$	$65° \pm 5°$	$65° \pm 5°$	$65° \pm 5°$	$65° \pm 5°$
Position of center (relative to Sgr A*)						
Right Ascension	$1''W \pm 1''$	$0'' \pm 1''$	$1''W \pm 4''$	$0'' \pm 2''$	$\approx 0''$	$\approx 0''$
Declination	$1''S \pm 1''$	$1''N \pm 1''$	$7''S \pm 7''$	$0'' \pm 2''$	$\approx 0''$	$\approx 0''$

[1] our parameters for the mini-spiral
[2] Lacy *et al.* (1991) for the mini-spiral
[3] Roberts & Goss *et al.* (1993) for the western arc
[4] Serabyn & Lacy *et al.* (1985) for the northern arm
[5] Serabyn & Lacy *et al.* (1985) for the western arc
[6] Serabyn *et al.* (1986); Güsten *et al.* (1987); Sutton *et al.* (1990) for the molecular disk

the central stellar cluster believed to be isothermal is 5×10^5 $(10^{\pm 0.3})M_\odot$, the core radius is (0.15 ± 0.05)pc (Eckart *et al.* 1993), the central point mass (a putative black hole?) is severely constrained to a value of the order of $10^5 M_\odot$. This upper limit is consistent with the other approaches employing various physical processes (Ozernoy 1992, 1993). A comparatively small central mass makes it understandable why the radial distance of the kink on the rotational curve turns out to be rather close to the core radius of the stellar cluster.

We note in passing that the shape of the generated spiral wave outside the corotation radius does scarcely depend upon a concrete hydrodynamical mechanism of its generation. In particular, Eq. (1) could be appropriate for other hydrodynamical mechanisms as well. For instance, in Fridman *et al.* (1994) we have explored in detail the generation mechanism associated with a jump in the surface density and have obtained the same rotation curve ($V_\varphi =$ const) outside 0.2-0.3 pc (and also the same total enclosed mass). The method employed here is only valid for the determination of the rotation curve outside the central 0.2-0.3 pc and therefore gives only an upper limit to the point mass.

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