The Minispiral in the Galactic Center revisited

Bernd Vollmer\textsuperscript{a,1} Wolfgang J. Duschl\textsuperscript{a,b}

\textsuperscript{a}Institut f"ur Theoretische Astrophysik, Tiergartenstr. 15, D-69121 Heidelberg, Germany
\textsuperscript{b}Max-Planck-Institut f"ur Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

Abstract

We present the results of a re-examination of a [Ne\textsc{ii}] line emission data cube ($\lambda 12.8\mu m$) and discuss the kinematic structure of the inner $\sim 3 \times 4$ pc of the Galaxy. The quality of [Ne\textsc{ii}] as a tracer of ionized gas is examined by comparing it to radio data. A three dimensional representation of the data cube allows us to disentangle features which are projected onto the same location on the sky. A model of gas streams in different planes is fitted to the data. We find that most of the material is located in a main plane which itself is defined by the inner edge of the Circum-Nuclear Disk in the Galactic Center. Finally, we present a possible three dimensional model of the gas streams.

Key words: accretion, accretion disks, Galaxy: center, ISM: clouds
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1 Introduction

The dynamic behavior of the gas in the inner few pc of the Galaxy is still a matter of debate and speculation. There is an almost disklike structure of neutral gas located around the Galactic Center (GC) (Güsten et al. 1987, Jackson et al. 1993) (Serabyn et al. 1986). This Circum-Nuclear Disk (CND) extends over a radial distance of more than 5 pc. It has an inner edge at about 2 pc from the GC. The predominantly molecular gas moves around the GC with a speed of $\sim 100 \text{km}\text{s}^{-1}$ corresponding to a Keplerian velocity for an enclosed mass of several $10^6 \text{M}_\odot$. Within the inner 2 pc ionized gas has been found (Lo & Claussen 1983) which has the appearance of a spiral and was therefore named the minispiral. The region within the CND is often referred to as Sgr A West. It can be separated into at least four different components (Lacy, Achtermann, & Serabyn 1991) which we will discuss below. The kinematics derived from the [Ne\textsc{ii}] data shows...
a possible close link between this ionized material and the molecular gas at the inner rim of the CND. Thus the outer part of the minispiral appears to be the ionized edge of the CND. Often the minispiral was thought to be not only of spiral shape in projection against the celestial sphere, but rather a true one-armed spiral. However, the kinematics derived from radio recombination line observations (Roberts & Goss 1993) indicated several different structures instead of one single spiral.

In this paper we re-examine the [Ne II] data and the kinematic information contained in it. First, we introduce the dataset that we use (Sect. 2), and evaluate its usability as a tracer of ionized gas by comparing it with radio recombination lines (Sect. 3). In Sect. 4, we describe our visualization technique which proved to be of paramount importance for our analysis. Section 5 is devoted to a discussion of the morphological details in the image of the minispiral. The model that we derive from the data is presented in Sect. 6, in the subsequent Section, we describe the three dimensional structure of the gas streams, and summarize our conclusions in Sect 9.

2 The data

We use the [Ne II] (λ12.8 μm) line emission observations described in detail by Lacy, Achtermann, & Serabyn (1991). The data cube was made available to us by Lacy. The observations were carried out using a mid-infrared cryogenic echelle spectrograph. The spectral dispersion was about 16.5 km s\(^{-1}\) per pixel, the spectral resolution being about 2 pixels FWHM. An area of 75" × 90" was mapped with 2" resolution. A [Ne II] line map was produced by summing over the channels covering Doppler shifts from +380 to −412 km s\(^{-1}\). This map is shown as a ruled-surface representation in Figure 1.

3 The comparison with the radio data

Roberts & Goss (1993) observed the Sgr A West complex in the H92α line at 8.3 GHz with a resolution of 1". As the data of the radio recombination line and the [Ne II] emission at 12.8 μm give both information about the distribution of the ionized gas, they should show the same features. Figure 2 shows the superposition of these data. As, at this point, we are
Fig. 2. Superposition of the 8.3 GHz data as a contour representation together with the \([\text{Ne}\,\text{ii}]\) line emission in a linear grey scale. Intensities greater than \(3 \times 10^{-3}\,\text{erg}\,\text{s}^{-1}\,\text{cm}^{-2}\,\text{sr}^{-1}\) are set to this value in order to emphasize the features. The point source Sgr A* is indicated with a cross.

not interested in fine details but in much more in the overall distributions, the different resolutions of the two datasets pose no problem. We find that the overall features are the same in both wavelengths indicating that

(1) there are no depopulation effects affecting the \([\text{Ne}\,\text{ii}]\) data,
(2) \([\text{Ne}\,\text{ii}]\) line emission is a good tracer for the ionized gas

4 Three dimensional visualisation

In the following, we will often use a three dimensional representation of the data using a normal Cartesian coordinate system with R.A. corresponding to the \(x\) direction, Dec. to the \(y\) direction and the local standard of rest (LSR) velocities to the \(z\) direction. To give a better visual impression, we have chosen to illuminate the shown surfaces from the observer's direction. In this representation features are the brighter the closer they are to the observer. The surfaces indicate pre-determined levels of constant intensity. To keep the figures as clear as possible, we give absolute numbers for the axes only in the color representation of Fig. 3.

5 The morphology

Lacy, Achtermann, & Serabyn (1991) discussed four separate morphological components in the Sgr A West complex:

(1) the Northern Arm which is the most prominent feature and runs approximately from the radio source Sgr A* (the Galactic Center) to the north;
(2) the Western Arc which is the bright, almost "vertical" rim in the west of Sgr A*;
(3) the Eastern Arm which runs from the north east to the east of Sgr A*; and
(4) the Bar which is situated "below" Sgr A* and shows a straight shape.

Applying the above described analysis technique, it becomes evident that at least for the Bar the structure is more complicated than previously thought. Figures 4 to 6 show the data cube rotated by 30° around the \(x\)- and \(z\)-axis for three different intensity levels. Figures 6, 7, and 8 give different viewing angles to allow
Fig. 3. A three dimensional representation of the data cube (radial velocity as a function of position on the sky. The velocities are color coded. In the bottom plane (R.A./Dec.), the projected mini-spiral is depicted. For an even clearer visualization of the 3D structure of the data cube, we also show it in an animation (URL: anim1.gif).

for a full appreciation of the three dimensional distribution.

The following features are marked:

(1) **The Northern Arm:** It appears as an almost vertical tube where material with the highest densities can be found. If one looks at Figure 5, it becomes apparent, that part of the high negative velocity end of this feature runs into the area of the Bar.

(2) **The Western Arc:** It represents the feature of lowest intensity, and as such appears only in the images of the data cube that trace the lowest intensities. There it can be seen as a
bent tube with a small velocity gradient.

3) **The Eastern Arm**: It appears to consist of two components. A vertical **finger** of high intensity and a large **ribbon** which extends to the east of Sgr A*.

4) **The Bar**: As the polarization measurements of Aitken et al. (1991) have already shown, this is the most complicated feature in the region. Looking at Figs. 4 and 5 it is clear that there are two distinctly different components which we will call **Bar 1** and **Bar 2**.

6  **The model**

For our model, we assume that the mass distribution in the inner few pc
Fig. 8. The same representation of the data cube as in Fig. 7, but rotated by 300° with respect to the z-axis. Under this angle, the Western Arc can be seen particularly well as a bright line of emitting material in the foreground.

of the Galaxy can be reasonably well approximated by a spherically symmetric ansatz:

\[ \frac{M(R)}{M_\odot} = \frac{M_0}{M_\odot} + 1.6 \times 10^6 \left( \frac{R}{\text{pc}} \right)^{1.25} \]  

(1)

with \( R \) the radius from the center of the Galaxy, \( M(R) \) the radial mass distribution, and \( M_0 = 3 \times 10^6 M_\odot \) the mass of the central black hole (Genzel et al. 1997); the radially dependent contribution is an interpolation given by von Linden, Duschl, & Biermann (1993) for radii smaller than a few hundred pc. We assume the gaseous material to flow on closed circular orbits in the gravitational potential of this mass distribution.

In order to allow for local turbulent motion (which however is assumed not to dominate the flow patterns), an additional random, however on average isotropic velocity component is introduced. This corresponds – through hydrostatic equilibrium – to a certain thickness of the different flow patterns.

As, at this point we are not heading for a self-consistent hydrodynamic model of the flow, we finally allow for an ad hoc radial accretion velocity of 5% of the local Keplerian azimuthal velocity is assumed. We find that the model is much more sensitive to the absolute values of this radial velocity than of the turbulent velocity. However, given that the accretion velocity has a specified preferred direction (inwards) while the turbulent velocity is isotropic, this is not really a surprise. In Fig. 9, we show the projected velocity vectors for a disklike flow with a turbulent velocity of 40% of the Keplerian velocity, and a turbulent velocity of 5% of the Keplerian velocity.

Choosing the turbulent velocity, i.e., the thickness of the disk, and the accretion velocity, in terms of an ac-
cretion disk model would be equivalent to prescribing the value of the viscosity. In terms of the standard theory of accretion disks (see, e.g., Frank, King, & Raine 1992), this corresponds to a viscosity parameter $\alpha \sim 0.3$, i.e., a value well within what one finds for other types of disks.

We now model the flow by searching for the minimum number of different planes that are required to cover the observed features in the data cube. This obviously requires us not to think in terms of completely filled accretion disks. What we have in mind is a much more transient phenomenon in the following sense: We assume that clumps of gas – undergoing some type of viscous interaction and/or tidal stretching – are falling towards the GC. Locally they are described by a flow with Keplerian plus turbulent plus accretion motion.

We find that the smallest number of planes to fit the whole measured data cube is three. One of them coincides with that of the CND. We will call that plane the main plane, or plane (i). In Tab. 1 we give the orientations of the three planes. While for a single planes, some uncertainty about the sign of the inclination angle would be left, for the ensemble of three planes the consistency indicates the correct choice.

To give an idea about the realtive orientations, in Fig. 10 we show the orientation of planes (i) and (iii). The arrows indicate the sense of rotation. The cross shows the position of SgrA*.

| plane | position | angle | inclination | closest edge |
|-------|----------|-------|-------------|--------------|
| (i)   |          | 28°   | 25°         | W            |
| (ii)  |          | 132°  | -15°        | SW           |
| (iii) |          | 115°  | 20°         | NE           |

plane (i) the disk’s velocity is positive for positive declination offsets and negative for negative declination offsets from Sgr A*. In the case of plane (iii) there are negative velocities for positive declination offsets and positive velocities for negative declination offsets. Thus one has a kind of counter-rotation of the material in plane (iii) with respect to that in plane (i).
7 Comparing the model with the data

In order to evaluate the quality of the model fit, we determine the residuals of the subtraction of the resulting model data cube from the observed one. At the same time, subtracting individual model planes from the entire observed data cube allows to demonstrate where individual structures are located. As an example, in Fig. 11 we show the data cube after subtraction of plane (i).

When performing this for all three planes, we find that

(1) the Western Arc, the Northern Arm and the Bar 1 are contained in plane (i), whereas the whole Eastern Arm and the Bar 2 are situated beyond;
(2) plane (ii) covers the Finger of the Eastern Arm and the Bar 2;
(3) the rest of the Eastern Arm is situated in plane (iii).

In Fig. 12 we give the residual between observed and model data cube after subtracting all three planes and projecting it onto the sky. The only remaining structures are a small part of the Eastern Arm and features in the immediate vicinity of the IRS8 complex in the north. All other structures can be represented well within our model of the flow being mainly confined to three planes.

This indicates that the Western Arc, the Northern Arm and the Bar 1 are
located in the main plane, i.e., the plane of the CND. What in projection appears a one structure called Eastern Arm seems to consist actually of at least two components, one of which lies in the same plane as the Bar 2, while the remainder is located in a different plane.

8 The distribution of the material in three spatial dimensions

With the knowledge gained in the previous Section, one can now invert the problem and determine the flow patterns in the three planes, independent of the projected features. In Fig. 13 do so for plane (i), the main plane which coincides with the plane of the CND. In the Fig., we show a view face-onto plane (i). It shows the Northern Arm at the left of the center, the Bar 1 at the right and the Western Arc which is bent from the end of the Northern Arm to a point below the center. Through projection an observer on Earth see the distribution shown in Fig. 14: One finds the shapes of the Northern Arm and the Western Arc.

The same procedures were repeated for planes (ii) and (iii). The results are shown in Figs. 15.

Figure 16 shows the combined projection of all three planes for an Earth-based observer providing a remarkably nice fit of the measured [Ne II] data.

Going to lower intensity levels, we find the possibility of a tenuous gas component which filling almost entirely plane (i). There are hints that this could also be the case for plane (ii), whereas the material in the third plain seems to form unconnected entities (Figure 17).

Finally, we give in Fig. 18 a view of the same data, however seen from a
Fig. 15. Contour representation the distribution of emitting material in planes (ii) and (iii). Both plans are shown face-on.

different angle (155° with respect to the $z$-axis) chosen such that planes (i) and (ii) are seen edge-on.

9 Conclusion

We have re-analyzed a $[\text{Ne} \, \text{n}]$ emission line distribution in the immediate vicinity of the GC by means of a three dimensional visualization of the data cube. We find that due to projection effects some physically distinct entities mislead us by appearing as single features. Based on the data cube, we have re-classified the structures in Sgr A West. We find that they are confined to mainly three distinct planes. Within the planes they represent the denser material. However, at least in two of the three planes, tenuous gas seems to fill almost the entire planes, not unlike accretion disks. Most of the minispiral’s material is located in a

Fig. 16. The ionized gas distribution of all three planes shown as an observer on Earth sees it.

Fig. 17. Same representation as in Fig. 16, however for a lower intensity level.
Fig. 18. The same data as in Figure 17 rotated by an angle of $155^\circ$ with respect to the $z$-axis. Plane (i) is seen vertically edge-on; plane (ii) is also seen edge-on. For an even clearer visualization of the 3D structure of the data cube, we also show it in an animation (URL: anim2.gif).

We find the best fit for material moving in the planes on Keplerian circular orbits, overlayed with a turbulent velocity component of some 40% of the Keplerian speed and an inwards radial velocity of 5% of the orbital velocity.

It is important to note that our fits exclude predominant outwards motion; it seems that a scenario of a mass stream from outside towards a central black hole is supported by our results. It is tempting to speculate that the different components that project as the minispiral onto the sky actually are chunks of matter "falling out of the CND towards the black hole" (see also Zhao & Goss (1999)). Then the presence of individual planes would be of little surprise. They are – more or less randomly – defined by the local angular momentum of the material leaving the CND. One expects – on average – a direction coinciding with that of the CND. However, as individual clumps may very well have an angular momentum that differs somewhat from the local average, for individual streams, planes different from that of the CND are possible. At the same time this tells us that these features are rather short-lived.

The three dimensional spatial reconstruction of the distribution of the matter moreover indicates that counterrotating features are present. At this point it is suggestive but not yet clear whether this has anything to do with the counter-rotating early type stars found by Genzel et al. (1996). One can – as a speculation – not even exclude that the material in plane (iii) is indeed the rest of the material out of which those stars were formed.

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