Sgr A* and its siblings in nearby galaxies

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Abstract. We have proposed previously that Sgr A* is simply a scaled down AGN with a black hole, an accretion disk and a radio jet operating at a very low power. It appears as if M81* – the nuclear source in the nearby galaxy M81 – is an ideal laboratory to study a Sgr A*-like source at a higher power level. The jet/disk model can explain M81* in great detail with no basic changes in the model parameters other than the accretion rate. Radio cores in other LINERs may be explained by the same model and they appear to be low-power counterparts to radio-loud quasar cores. For Sgr A*, models without a supermassive black hole are facing difficulties – some of which are discussed here, but a persistent puzzle in any scenario are the non-detecions and low flux limits for Sgr A* from IR to x-rays. Especially the IR limits are a threat to accretion models. I discuss whether a thin molecular disk (as seen in NGC 4258) around Sgr A* could intercept infalling material before it reaches the black hole.

1. Introduction

The Galactic Center (GC) is a unique place in our galaxy, however, it is not necessarily a unique place in the universe. For this reason the GC has often been used as an anlogy for other galaxies, and the GC can help us to understand what we do not understand in more distant places. But for some aspects of the GC itself, the GC is not necessarily the best place to look for answers.

The latter is especially true for the central compact radio nucleus Sgr A*. While its basic radio properties are known for quite a while, the search for counterparts in other wavelength regimes has been largely unsuccessful. This is mainly due to the intrinsic weakness of the Galactic Center and the obscuration in the Galactic plane. Those difficulties have in part driven the developments of many new instruments and techniques – the GC is often among the first objects to be observed with new cameras. And once in a while this has led to a detection of Sgr A* at frequencies inaccessible to radio astronomers (e.g. IR, NIR, X-rays, 511 keV line, etc.), but whenever the next generation of instruments provided higher sensitivity and resolution, it was shown that this emission was due to stellar objects and not due to the suspected supermassive black hole in the very center. This means that any successful model for Sgr A* has not only to be self-consistent but must also be stable against the annual variations in detections of Sgr A* which are a function of wavelength and spatial resolution. Fortunately, at least the evidence from dynamical estimates for the presence of a dark mass of $M_\bullet = 2 \cdot 10^6 M_\odot$ in the center of the Galaxy has become more and more convincing (Genzel 1996, Rieke & Rieke 1996, Haller et al. 1996) in recent years and now seems well established.

The presence of such a large concentration of dark mass in the very nucleus of the Galaxy places the GC in line with many other galaxies where similar or even much higher dark mass concentrations have been found (Kormendy & Richstone 1995). Another similarity to other Galactic Nuclei is the presence of a compact flat spectrum radio core which is found in all radio loud active galaxies, as well as in many other active galaxies like radio quiet quasars, Seyferts, LINERs, in many elliptical galaxies, and also in some spiral galaxies. In this respect is the Galactic Center fairly typical and therefore should not be considered as an isolated case. In this paper I will therefore not only discuss possible explanations for Sgr A* and their difficulties, but also apply our Sgr A* jet/disk model to other weakly active galaxies, specifically to the nucleus of M81.

2. Modelling Sgr A*

2.1. What we see...

Sgr A* is constrained by what we see and also by what we do not see. The size and spectrum of the radio core are the primary input data to all models, but even though this is one of the few things we see, both are controversial in some details. The size of Sgr A* is dominated by scatter broadening at frequencies at least up to 22 GHz and the smallest sizes reported so far are 1.7-2.8 AU (Doelemann et al. 1996, Rogers et al. 1994, Krichbaum et al. 1994) at λ3mm. The overall spectrum of Sgr A* is inverted. While Duschl & Lesch (1994) claim a spectral shape of $\nu^{1/3}$ from cm to submm wavelengths, Mark Morris presented during the conference a spectrum of Sgr A* which was taken within 2 weeks by the CSO/JCMT/OVRO collaboration and the VLA, indicating that the cm part may be fitted by a single powerlaw, while the submm part shows a submm-excess. The possibility of a submm-excess has been around for quite a while (Zylka et al. 1992) but due to the variability of Sgr A*, which is well established in the radio regime, it was never unambigiously proven. A clear experiment to demonstrate this, would be truely simultaneous cm/mm/submm observations of the GC, and preparations for such a campaign are on the way.

The importance of the submm-excess is that, if it exsists, it implies synchrotron self-absorption at frequencies around 100 GHz, and as shown e.g. in Falcke (1996a) this requires an ultra compact region of ~ 0.1 AU. Given the mass of $2 \cdot 10^6 M_\odot$ this size translates into a region which is only 2-3 Schwarzschildradii in diameter. A proper determination of the mm/submm spectrum of Sgr A* could fix this number to a relatively high degree. Consequently, if there really is a black hole, a future global submm VLBI experiment would be able to probe a region which is strongly affected by General Relativistic effects. Light bending and assymmetries due to the Kerr Metric could in principle be directly imaged. Even though the technical realization of such an experiment may be decades ahead, the principal feasibility warrants a lot of excitement and motiviation for future work in the GC – we do not know many other places, if any at all, where such an experiment might ever become possible.

Observations of the better known cm part of the spectrum reveal kinks (Wright & Backer 1993) and strongly varying spectral indices (Zhao et al. 1996, in prep.) which requires synchrotron self-absorption also at lower frequencies and argues for a stratified medium in Sgr A* rather than a single component model. In fact, this is what most models for Sgr A* actually imply; and because the observed quantities of Sgr A* are so few, but very constraining, the published Sgr A* models do not really differ in their underlying physical processes. The basic ingredients of these models are a black hole and an accretion flow, a certain conversion factor between the accretion power and the non-thermal emission, and various equipartition arguments. In the Bondi-Hoyle accretion model of Melia (1992 & 1994) and in the advection dominated disk model by Narayan et al. (1995) the radiative efficiencies are fairly low and the emission mechanism for Sgr A* is cyclotron/synchrotron emission, while in the jet/disk-symbiosis model by Falcke et al. (1993a) the radiative efficiency is fairly high and the emission mechanism is pure synchrotron radiation. In the former cases one has pure inflow, in the latter case one has inflow and outflow. Duschl & Lesch (1994) proposed a stationary, homogenous blob of synchrotron radiating monoenergetic electrons, which they qualitatively link to an accretion disk.

2.2. ... and what we do not see

As mentioned above, the basic theme for all models so far is accretion onto a supermassive black hole and it is very difficult to avoid strong thermal radiation from the accretion flow. Not long ago it was thought that a substantial fraction of the central luminosity of $10^7 L_\odot$ in the GC is produced by this process. Alas, it is now apparent that the stars we see are enough to produce the bulk of this luminosity and the heating of the ambient medium and the CND (e.g. see Latvakoski et al. 1996). The hope that some thermal emission from Sgr A* had been discovered at least in the NIR (Eckart et al. 1992) also faded recently with improved astrometry and resolution (Genzel 1996). Hence, there is currently *no direct evidence for any thermal emission from Sgr A**. That may not mean much, because there are also many luminous O/B stars in the GC which we cannot see, just because of obscuration. Nevertheless, the contraints on accretion disks are severe. The current NIR limits and mass estimates of the black hole require accretion rates to be $< 10^{-8} M_\odot$/yr for a standard accretion disk (see Falcke et al. 1993a). On the other hand Melia (e.g. 1992) has argued that a supermassive black hole in the GC should accrete of the order $10^{-4} M_\odot$/yr from stellar winds. He suggested spherical accretion and the formation of only a small transient disk, Narayan et al. (1995) have proposed that the accretion disk is advection dominated and therefore more than 99.9% of the energy is advected and never radiated. With the ever decreasing limits on the dereddened Sgr A* flux of less than 20mJy (inferred from Eckart et al. 1995), however, the "inefficiency levels" for the latter two models become uncomfortably high, while the accretion rate for standard accretion disk models also become uncomfortably low (even though I have to admit that "comfort" is not really a well defined physical quantity).

2.3. Spherical accretion and fossil disk

Recently we have proposed another alternative (Falcke & Melia 1996) which builds up on the suggestion by Falcke & Heinrich (1994) that Sgr A* might well be surrounded by a fossil accrection disk — a remain of past activity. Such a fossil disk (or ring) may be very optically thick, very stable over a long time and could in principle capture infalling matter at a large radius, possibly without producing the amount of luminosity usually expected if the matter were to fall into the very center. The disk would not be disrupted by the infalling wind because it could still be very massive. The dynamical timescale of the fossil disk is much shorter than the time scale for the infall, which is given by the ratio $\dot{\Sigma}_{\rm wind}/\Sigma_{\rm disk}$ between the mass deposition rate per unit area and the surface density of the disk.

To study this process in more detail, we have modified the standard accretion disk equations to allow for matter and angular momentum deposition, and have calculated the time evolution and spectrum of such an accretion disk. In a second step we have coupled this accretion disk model with 3D hydrodynamical calculations of a Bondi-Hoyle flow (Coker et al. 1996). This allowed us to test which scenario might be compatible with current observations. The boundary condition was that the high mass inflow that had been intercepted at a large radius should not propagate into the center within a couple million years — the presumed age of the high mass-loss star — and the luminosity should not exceed the current IR/NIR and total luminosity limits.

The first result is that it is *not* possible to hide any strong inflow with zero angular momentum. While indeed a lot of the wind is captured by the fossil disk at larger radii, the remaining part of the wind is still too large and would produce an enormous amount of luminosity. Another problem with a zero angular momentum wind is that even if it is absorbed at a large radius, the kinetic energy dissipated in the impact will produce strong emission.

Therefore, one has to invoke a non-zero angular momentum wind, which circularizes at a large radius. We find that a minimum radius for the circularization need to be of the order $R_{\rm circ} \gtrsim 10^{16}$ cm (i.e. 0.1"), but could of course be larger. The viscous timescale for changes in such a structure could be as long as several 10-100 Million years. The resulting spectrum differs substantially from a normal accretion disk spectrum and shows a strong peak in the IR. A complication for the modelling is that the accretion radius of the Bondi-Hoyle flow is 10^{17}cm and therefore any fossil structure of the size discussed here might already start to influence the whole Bondi-Hoyle structure and the bow shock. Another problem is that the Bondi-Hoyle spherical accretion solution changes if one adds angular momenum to the flow, the wind which is finally captured does not retain the same specific angular momentum it had before it encountered the black hole. Therefore one can not easily translate an uneven, or rotating source distibution into an angular momentum of the infalling wind.

From Maser observations of NGC 4258 (Miyoshi et al. 1995) we know that molecular disks exists on such small scales. But the structure we have discussed for Sgr A* so far is pure fantasy and was born out of the need to explain what we do not see, and is not based on any positiv detection. Nevertheless, if present a fossil disk should of course have observational consequences, especially in the IR. Stolovy et al. (1996) have announced the detection of a source at 8.7μm with dereddened flux of ~ 100 mJy at the position of Sgr A*, but at the current resolution a direct association with Sgr A* in this crowded and tricky field is by no means certain. Such a flux would correspond to a black-body disk with radius 10^{15} cm, inclined by 80° at a temperature of 350°K (not quite room temperature but close). A disk with $R \sim 10^{16}$cm at that temperature would already produce too much flux. This shows that the current limits for such a configuration are already very tight.

2.4. Are there alternatives?

With the problems currently troubling accretion models one is tempted to ask whether there are alternative models for Sgr A*. Is there a life without a black hole? Can we replace the black hole with an ultradense cluster of stellar remnants? Well, it wouldn't be much fun in the first place. Secondly, while one may find alternative solutions by just considering the emission properties it becomes very difficult if one takes the whole context into account. There is for example the observation by Backer (1996) that Sgr A* does not move w.r.t. to the Galactic Center, while any low mass object should (as we now see directly in the stars). The total mass of Sgr A* therefore needs to be at least several 100 $M_\odot$ and this mass can obviously not be in the synchrotron radiating gas, so that we need an anchor of at least several hundred, possibly thousand, stellar remnants. On the other hand we need at least $10^{3.5}L_\odot$ for the synchrotron radiation alone. If we assume that this energy comes from accretion onto this hypothetical central cluster we have to have at least an accretion rate of $10^{-4}M_\odot$/yr. The minimum size scale for Sgr A* is 10^{12}cm (see Falcke 1996a) and the radiative efficiency for a 1000 $M_\odot$ object at this scale is only $6 \cdot 10^{-5}$, because we are not very deep in the potential well. However, if the accretion continues onto the stellar remnants, they would inevitably turn into strong x-ray emitters. In fact, a fraction of only 10^{-6} of this accretion rate would be enough to violate all current x-ray limits (see Koyama et al. 1996, Maeda et al. 1996).

Can we then power Sgr A* without accretion, e.g. if the plasma is heated in some mysterious way by the kinetic or potential energy of the supposed stellar remnants? The problem here, as well as for the accretion scenario above, is that the pressure one derives for the synchrotron radiating gas in Sgr A* (especially in the submm where we have $n \sim 10^4\mathrm{cm}^{-3}$, $B \sim 10$G, $r \sim 10^{13}$ cm, see e.g. Falcke 1996a) would require a central mass of $10^{8-9}M_\odot$ to keep it in the center — otherwise it would literally be blown away within seconds, just like in the jet-model (see also an earlier discussion in Reynolds & McKee 1980). A cluster of stellar remnants would never have enough potential energy to keep the gas in the center. Consequently, even if there are a bunch of stellar remnants throughout the central star cluster as suggested by Haller et al. (1996), Rieke & Rieke (1996), and Saha et al. (1996) it appears very unlikely that they have anything to do with Sgr A* itself.

3. The siblings

3.1. M81*

We are strongly limited in our modelling of Sgr A* by two important effects: scatter broadening and obscuration. Thus we know neither the intrinsic shape and size of Sgr A*, nor its optical/UV properties. However, as mentioned in the beginning, any model for Sgr A* should be invariant to translation by at least a few Mpc. Therefore, it seems as if the best place to learn more about Sgr A* is the nucleus of M81 (see Falcke 1996b). This is a spiral galaxy, classified as a LINER, where we are not strongly affected by obscuration. In the nucleus we find a compact flatspectrum radio core (which we call M81* in analogy to Sgr A* and M31*) with a size of 550 AU at 22 GHz and an inverted spectrum ($F_\nu \propto \nu^{0.2\pm0.2}$, see Reuter & Lesch (1996) and references therein). Unlike Sgr A*, this core is resolved with VLBI at various frequencies and shows a size proportional to $\nu^{-0.8\pm0.05}$ (Bietenholz et al. 1996, and references therein), hence it is not scatter broadened. Moreover, the core is elongated and one finds structure with the VLA at a much larger scale in a similar direction. The most likely explanation for this observation is the presence of a jet.

The bolometric luminosity of the M81 nucleus has been estimated to be of the order $10^{41.5}$ erg/sec (Ho et al. 1996) and Bower et al. (1996) recently discovered broad double-peaked Hα emission from M81, which is either due to an accretion disk or a bi-polar outflow.

With this information it was of course tempting to apply the jet/disk symbiosis model we developed initially for Sgr A* (Falcke et al. 1993b) to M81*, at least here it is much easier to argue that a mini-AGN with jet and accretion disk really is present. Especially the detailed VLBI informations allow a more detailed test of the model.

The first important point is the frequency dependence of the size, with a size index $m = -0.8 \pm 0.05$ ($r \propto \nu^m$) and an inverted spectrum. The frequency dependence of the size was one of the basic predictions of the jet model, while in homogenous, optically thin models (e.g. Duschl & Lesch 1994) a constant size is expected – this reflects the main differences between homogenous and inhomogenous (i.e. with gradient in magnetic field) models.

However, the extremely simplified jet emission model also does not fit perfectly, as it predicts a flat ($\alpha = 0$) rather than an inverted spectrum, and the predicetd size index is $m = -1$, thus slightly steeper than observed in M81*. It is of course fairly easy to modify the jet model to fit those values, e.g. by imposing a certain non-conical jet shape (as it is frequently done for quasar cores). Such a non-conical shape would imply external confinement or acceleration of the jet. On the other hand those models usually lack a physical justification for the acceleration or collimation (especially with the high internal pressures involved) and it makes one feel uncomfortable to just add another arbitrarily chosen input parameter for each new observed quantity. Fortunately, it turned out that there is a slight inconsistency in the canonical Blandford & Königl (1979) jet model used previously (e.g. Falcke & Biermann 1995), where one usually neglects the dynamical effects of the pressure gradient on the velocity field of the jet flow. If calculated self-consistently this pressure gradient will indeed lead to a slight acceleration of the jet. In terms of the velocity structure this is a weak effect,

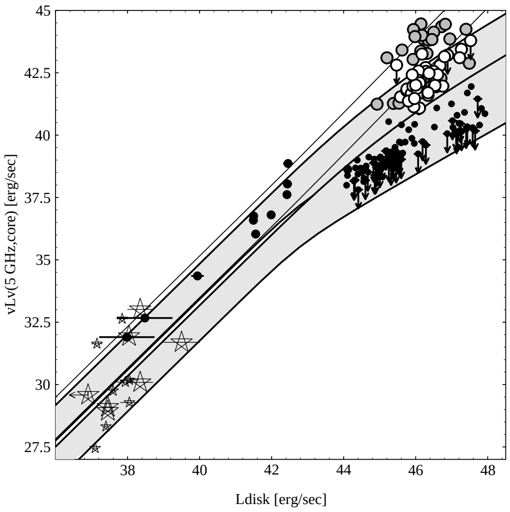

Figure 1. Radio core vs. bolometric nuclear luminosity for a variety of known and putative jet/disk systems (from Falcke & Biermann 1996a) and the predicted distributions from the jet/disk symbiosis model. The stars in the lower left are galactic jet sources and x-ray binaries, circles and dots in the upper right are radio loud and radio quiet quasars. Black dots below $L_{\rm disk} = 10^{44}$ erg/sec are LINERs and Sgr A* and M31* – it appears as if LINERs could be the missing link between highly active radio loud quasars and almost inactive, yet radio-luminous, nuclei like Sgr A*.

however, if one starts with a fully relativistic gas (i.e. sound speeds of the order $0.6c$ – something neccessary to escape from the inner parts of a black hole) it is just enough to make the jet mildly relativistic ($\gamma_{\rm j} \simeq 2-3$). Due to the boosting effect, the emission at lower frequencies, coming from more distant regions, will be Doppler-*dimmed* w.r.t. the higher frequencies for most aspect angles and thus yield an inverted spectrum and a flatter size index.

For the given luminosity of M81* and the jet-power/disk-luminosity ratio we found for quasars (see Falcke et al. 1995), the whole Sgr A* jet/disk symbiosis model can then be boiled down to a two parameter model, where we need only the electron Lorentz factor $\gamma_{\rm e}$ and the inclination angle i as an input parameter, which on top of that, are both fairly well constrained.

And in fact, for $\gamma_{\rm e} = 220$ and $i \simeq 30-40°$ the model predicts the observed size (550 AU at 22 GHz), flux (110 mJy at 22 GHz), spectral index ($\alpha = 0.17$), and size index ($m = -0.9$) for M81* reasonably well. Sgr A* can be explained by the same model for an assumed $L_{\rm disk} \sim 10^{39}$erg/sec with $i \sim 60° - 70°$ and $\gamma_{\rm e} = 140$, the predicted average spectral index is $\alpha = 0.23$ and $m = -0.9$ — the size of the major axis should be around 6 AU at 7mm.

3.2. The rest of the family

It is interesting to note that we had to use a *radio-loud* model (defined by the radio/$L_{\rm disk}$ ratio) to explain M81* (the same is true for Sgr A* and possibly

M31*). Could it be that the cores of radio loud quasars have their low-luminosity counterparts in LINERs and other weakly active galaxies? For this reason we have begun to revisit the radio properties of some nearby galaxies with signs of nuclear activity; quite a few have compact flat-spectrum radio cores similar to Sgr A* and M81*, e.g. like the Sombrero galaxy (M104). Unfortunately, due to the low level of activity, the determination of a bolometric or "disk"-luminosity for the nuclei can be very difficult. Bearing that in mind, we have plotted the radio core fluxes of a small sample of prominent galaxies versus what we estimate to be their disk luminosity in Fig.1. Those results are of course very preliminary and need further refinement, nevertheless, it is quite interesting that the cores of those LINER nuclei all seem to fall on the radio-loud branch of the jet/disk symbiosis model, and some of them, like NGC 1097, do indeed have well known jets. This could mean that basically all those radio cores in LINERs are the bases of radio jets and they could be the missing link between Sgr A* and radio loud quasars. Further study of those radio cores in the Galactic Center and elsewhere might therefore not only reveal something about the true nature of Sgr A*, but also help us to understand the radio-loud/radio-quiet dichotomy in quasars.

4. Conclusion

All the models proposed for Sgr A* have a certain appeal. The jet/disk model – with and without monoenergetic electrons – offers a scope that goes far beyond the GC and has survived a series of critical tests in a variety of very different source classes with compact flat spectrum cores, including Sgr A*. Advection-dominated and fossil disks may help to explain why the optical luminosity of Sgr A* is so low, and Bondi-Hoyle accretion is a process that seems to be unavoidable at a certain level. Applying all these concepts to the nuclei of nearby galaxies may help us to sort out which process dominates in which regime. Until then we perhaps could agree on a "theorists-for-galactic-peace-model" for Sgr A*: a jet of monoenergetic electrons, produced by an advection dominated disk comming from a fossil ring which is fed by Bondi-Hoyle accretion.

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References

Backer D.C. 1996, in "Unsolved Problems of the Milky Way", IAU Symp. 169, L. Blitz & Teuben P.J. (eds.), Kluwer, Dordrecht

Bietenholz, M.F., Bartel, N., Rupen, M.P., Conway, J.E., Beasley, A.J. et al. 1996, ApJ 604, 28

Blandford R.D., Königl A. 1979, ApJ 232, 34

Bower, G.A., Wilson, A.S., Heckman, T.M., Richstone, D.O. 1996, AJ 111, 1901

Coker R., Melia F., Falcke H. 1996, to be submitted to ApJ

Doeleman S., Rogers A.E.E., Bower G.C., Wright M.C.H., Backer D.C. 1995, BAAS 187, #12.14

Duschl W.J., Lesch H. 1994, A&A 286, 431

Eckart, A., Genzel, R., Krabbe, A., Hofmann, R., van der Werf, P. P., Drapatz, S. 1992, Nat 355, 526

Eckart, A., Genzel, R., Hofmann, R., Sams, B.J., Tacconi-Garman, L.E. 1993, ApJ 407, L77

Eckart, A., Genzel, R., Hofmann, R., Sams, B.J., & Tacconi-Garman, L.E. 1995, ApJ 445, L23

Falcke H., 1996a, in "Unsolved Problems of the Milky Way", IAU Symp. 169, L. Blitz & Teuben P.J. (eds.), Kluwer, Dordrecht, p. 163

Falcke H., 1996b, ApJ Letters, Vol. 464 (June 10)

Falcke H., Biermann P.L. 1995, A&A 293, 665

Falcke H., Biermann P.L. 1996, A&A 308, 321

Falcke H., Heinrich O. 1994, A&A 292, 430

Falcke H., Melia F. 1996, to appear in ApJ

Falcke H., Biermann P. L., Duschl W. J., Mezger P. G. 1993a, A&A 270, 102

Falcke H., Mannheim K., Biermann P. L. 1993b, A&A 278, L1

Falcke H., Malkan M., Biermann P.L. 1995, A&A 298, 375

Genzel R. 1996, this volume T. 1991, ApJ 381, L43

Haller J., Rieke, M., Rieke, G., Tamblyn, P. Close, L. & Melia, F. 1995, Ap.J., in press

Ho L.C., Filipenko, A.V., & Sargent, W.L.W. 1996, ApJ 462, 183

Krichbaum T.P., Schalinski C.J., Witzel A., Standke K., Graham D.A., and Zensus J.A. 1994, in "The Nuclei of Normal Galaxies: Lessons from the Galactic Center", eds. Genzel R. & Harris A.I., Kluwer, Dordrecht

Kormendy J., Richstone D. 1995, ARA&A 33, 581

Koyama K., Maeda Y., Sonobe T., Takeshima T., Tanaka Y., Yamauchi S. 1996, PASJ 48, in press Astronomy - first results from ASCA, Universal Academy Press, p. 181

Latvakoski H., Stacey G., Hayward T., Gull G. 1996, this volume

Maeda Y., Koyama K., Sakano M., Takeshima T., Yamauchi S. 1996, PASJ 48, in press

Melia F. 1992, ApJ 387, L25

Melia F. 1994, ApJ 426, 677

Miyoshi M., Moran J., Herrnstein J. et al. 1995, Nat 373, 127

Narayan R., Yi I., Mahadevan R. 1995, Nat 374, 623

Reuter, H.-P., & Lesch, H. 1996, A&A subm

Reynolds S.P., McKee C.F. 1980, ApJ 239, 893

Rogers A.E.E., Doeleman S., Wright M.C.H. et al. 1994, ApJ 434, L59

Stolovy S.R., Hawyard T., Herter T. 1996, this volume

Wright M.C.H., Backer D.C. 1993, ApJ 417, 560

Zylka R., Mezger P.G., Lesch H. 1992, A&A 261, 119