



Publications of the Astronomical Society of Australia

VOLUME 18, 2001

© ASTRONOMICAL SOCIETY OF AUSTRALIA 2001

*An international journal of
astronomy and astrophysics*



For editorial enquiries and manuscripts, please contact:

The Editor, PASA,
ATNF, CSIRO,
PO Box 76,
Epping, NSW 1710, Australia
Telephone: +61 2 9372 4590
Fax: +61 2 9372 4310
Email: Michelle.Storey@atnf.csiro.au



For general enquiries and subscriptions, please contact:

CSIRO Publishing
PO Box 1139 (150 Oxford St)
Collingwood, Vic. 3066, Australia
Telephone: +61 3 9662 7666
Fax: +61 3 9662 7555
Email: pasa@publish.csiro.au

Published by CSIRO Publishing
for the Astronomical Society of Australia

www.publish.csiro.au/journals/pasa

Filaments in the Galactic Centre — with Special Reference to the ‘Snake’

Geoffrey V. Bicknell^{1,2} and Jianke Li^{1,3}

¹Research School of Astronomy & Astrophysics, Australian National University,
Mt Stromlo Observatory, Cotter Road, Weston, ACT 2611, Australia
Geoff.Bicknell@anu.edu.au

²Department of Physics & Theoretical Physics, Australian National University,
Canberra, ACT 0200, Australia

³Department of Mathematics, Australian National University, Canberra,
ACT 0200, Australia*

Received 2001 July 20, accepted 2001 October 22

Abstract: The non-thermal filaments in the Galactic centre constitute one of the great mysteries of this region of the Galaxy. We summarise the observational data on these filaments and critically review the various theories which currently outnumber the observed filaments. We summarise our theory for the longest of these filaments, the Snake, and discuss the relevance of this model for the other filaments in the Galactic centre region. The physics involved in our model for the Snake involves much of the physics that has dominated the career of Professor Don Melrose. In particular, the diffusion of relativistic electrons in the Snake is determined from the theory of resonant scattering by Alfvén waves.

Keywords: galaxies: interstellar matter — galaxies: the Galaxy — magnetic fields — star formation

1 Introduction

We would like to thank the organisers of this Festschrift for Professor Don Melrose for the opportunity to contribute this paper, summarising our recent research (Bicknell & Li 2001) on one of the mysterious filaments in the Galactic centre, known as the Snake. First, however, on this occasion, we would like to record a few personal notes based on our somewhat different interactions with Don Melrose. Geoff first met Don, when he took up his first appointment at Mt Stromlo and Siding Spring Observatories (now the Research School of Astronomy and Astrophysics) at the Australian National University. Geoff had started working on extragalactic jets at that time and this clearly involved the physics of particle acceleration on which Don was an expert and he was not. When Geoff started at Mt Stromlo he contacted Don, and the result of the ensuing collaboration was a paper (Bicknell & Melrose 1982) that created a lot of interest and half of which he would still defend today. Which half? The half that clearly sets out the relationship between hydrodynamic turbulent input and its dissipation via particle acceleration at the high wave number end of a turbulent cascade, to which they both contributed. That collaboration with an outstanding scientist was one of the most memorable experiences of his career at that time and one that he always looks back upon with satisfaction. Jianke worked in the ARC Special Research Centre for Theoretical Astrophysics that Don headed from 1991 to 2000. Jianke was impressed with Don’s vision for creating a career path for young theoretical astrophysicists and with

his capacity for research and administration. Jianke also wrote a paper with Don on pulsar magnetospheres (Li & Melrose 1994) and during the course of this work was impressed by Don’s strongly focused approach to science, by his physical insight, and by his insistence on understanding a problem fully at every stage. We both wish Don well in continuing his wide interests in astrophysics, and in his new and challenging position as head of the School of Physics at Sydney University. We trust that he will continue to contribute to astrophysics well into the future.

The work that is the subject of this paper fortuitously involves physics to which Don has made significant and enduring contributions. Our work on the curious filament in the Galactic centre known as the Snake involves the following:

- magnetic fields
- particle acceleration
- resonant scattering of relativistic particles and the diffusion of relativistic particles in the interstellar medium (ISM)
- a strong connection with solar physics

Those of you who are familiar with Don’s work will know that he has contributed significantly to all of these areas. The observations of the Snake also involved the outstanding PhD thesis work of Sydney University student Andrew Gray and his advisors and colleagues Professor Lawrence Cram, Professor Ron Ekers, Dr Miller Goss, and Dr Jenny Nicholls. The Snake was discovered through observations with the Molonglo Synthesis Telescope (Gray et al. 1991). It is therefore doubly appropriate to discuss this work on this occasion.

* Current address: Higher Education, Department of Education, Training and Youth Affairs.

In this paper, as well as summarising the work in our recent ApJ Letter (Bicknell & Li 2001), we have taken the opportunity to review some of the recent theoretical papers on the filaments, to expand some of the details in our own recent paper, to extend the treatment of relative timescales by incorporating a discussion of the important constraint imposed by synchrotron cooling, and to indicate where the physics discussed in this paper may relate to the Galactic centre filaments as a whole.

2 Filaments in the Galactic Centre

The Snake is one of a number of filaments in the central ~ 100 pc of the Galaxy that are regarded as some of the ‘major mysteries’ of the Galactic centre. The first set of such filaments, and by far the most visually spectacular, the ‘Arc’, was discovered by Yusef-Zadeh, Morris, & Chance (1984). Since that seminal discovery a number of other filamentary systems have been discovered — many with quite prosaic names such as the ‘Threads’ (Morris & Yusef-Zadeh 1985; Lang, Morris, & Echevarria 1999), the ‘Snake’ (Gray et al. 1991, 1995), and the ‘Pelican’ (Anantharamaiah et al. 1999; Lang et al. 1999). (For an impressive panoramic view of the Galactic centre at a wavelength of 90 cm, showing a number of these filaments, see the image in LaRosa et al. (2000).) The Snake was discovered in a survey carried out at the Molonglo Synthesis Telescope and has been the subject of a recent paper by us (Bicknell & Li 2001). However, an account of our model for the Snake would be incomplete without a discussion of the context in which this work was done. Therefore, in this section we give a brief review of the observational and theoretical work that has been carried out on these curious filaments. In the following section we separately address one of the outstanding issues raised by the observations — the strength of the magnetic field in the inner 100 pc of the Galaxy. For a comprehensive review of the observational and theoretical situation up until 1996 see the review by Morris & Serabyn (1996).

2.1 Observations

The main observational characteristics of the filaments observed in the central regions of the Galaxy are:

1. They are narrow. Generally the filaments are about a fraction of a parsec in transverse extent. The Arc is wider than this, ~ 5 pc, but breaks up into a number of subfilaments each a fraction of a parsec in width and separated by about 0.5 pc (Yusef-Zadeh & Morris 1987).
2. The emission is non-thermal, highly linearly polarised, and the magnetic field is aligned along the filaments.
3. There are substantial rotation measure variations associated with the environments of the filaments.
4. There is a wide variety in spectral index characteristics. The Arc has an inverted spectral index, $\alpha \approx -0.3$ ($F_\nu \propto \nu^{-\alpha}$). However, this steepens considerably away from the Galactic plane where the Arc degenerates into a more diffuse structure — the northern

and southern plumes (Reich 1990; Pohl, Reich, & Schlickeiser 1992). Most of the various isolated non-thermal filaments usually have a steeper spectral index, $0.6 < \alpha < 0.4$, at frequencies below 1.4 GHz that is consistent with what is usually observed for optically thin non-thermal spectra. The spectral index is steeper, $\alpha > 1.5$, at frequencies higher than 5 GHz. If the break in spectral index at ~ 5 GHz can be attributed to synchrotron cooling in a $\sim$ mG field, then the implied age $\sim 2 \times 10^4$ yr. The Snake is singular in that the spectral index has a conventional value, $\alpha \approx 0.4-0.5$, near the kinks in its structure, but this flattens with distance away from the major kink.

5. When imaged at high resolution, many filaments have a multi-stranded appearance. Yusef-Zadeh, Wardle, & Parastaran (1997) found that the filamentary system G359.54+0.18 is double and that the polarised emission is greatest where the two filaments appear to cross each other. Lang et al. (1999) found that both the northern and southern Threads have bifurcated regions and the northern Thread becomes diffuse at its northwestern extremity. The Pelican (G358.85+0.47) consists of multiple parallel strands which also become more evident near its ends (Lang et al. 1999). The Snake shows a bifurcation at its major kink (Gray et al. 1995). In some cases the filaments appear to be braided, e.g. the filaments associated with the HII region, Sagittarius C (Liszt & Spiker 1995).
6. Almost all of the filaments, except the Pelican, are aligned close to perpendicular to the Galactic plane. This has been taken by some to indicate a large scale poloidal $\sim$ mG field in the Galactic centre region and Lang et al. (1999) have suggested that the Pelican may mark a transition region of magnetic orientation some 225 pc in projected distance from the centre of the Galaxy.

A feature that these filaments have in common is that they all seem to involve magnetic fields that are strong compared to what we are used to in the ISM. This has led to suggestions of a large scale, high strength ($\sim$ mG) magnetic field in the Galactic centre region (e.g. Morris 1998). On the other hand, Roberts (1999) has pointed out that the field strengths are of the order that is estimated in the cores of molecular clouds and that observation is more consistent with the theory for the Snake that we outline below. The issue of the strength of the magnetic field in the Galactic centre region is discussed in Section 3.

2.2 Theory

There have been numerous widely different physical theories advanced for the filaments in the Galactic centre. Indeed the number of theories exceeds the number of filaments, surely representing a triumph of the inventiveness and creativity of the human spirit! Such a situation is also characteristic of a subject in its infancy. A number of theories for the Galactic filaments were reviewed by

Gray et al. (1995). Here we concentrate on some of the more recent attempts but also include some of the older models that have survived to the present or which have played a significant role in our attempts to understand these filaments.

The theories form naturally into a number of classes:

1. Star-based models incorporating some form of interaction of a star or cluster of stars with the ISM.
 2. Interaction of a hypothetical galactic wind with molecular clouds.
 3. Interaction of moving molecular clouds with a large scale $\sim$ mG magnetic field.
 4. Electrodynamic models:
 - (a) conventional MHD models involving the transport of magnetic field in the flux freezing approximation together with reconnection at specific locations
 - (b) unconventional models focusing on the currents produced by electric fields interacting with clouds and the subsequent generation of magnetic fields and instabilities
- (Classifying electrodynamic models in this way is not meant to imply any *a priori* value judgement on the relative merits of such models.)
5. Shock waves in the ISM.
 6. Morphologically unusual supernova remnants.
 7. Exotic models. An example is the proposal that cosmic strings are responsible for the filaments.

In all but the last class, magnetic fields are implicated. In some of the magnetic field models, the field is initially $\sim 10 \mu\text{G}$ and is amplified by some process or other; in others, a large $\sim$ mG magnetic field pervading the Galactic centre region is assumed.

Following Rosner & Bodo (1996), we list the following criteria that a successful model of the filaments has to satisfy:

1. *Energetics*. There needs to be a physical mechanism for the acceleration of relativistic electrons and this has to account for the luminosity of each filament.
2. *Spectrum*. As we have seen, the spectra of the filaments are quite varied. A good model should account for this variation as well as the individual cases.
3. *Geometry*. A mechanism for the generation of filamentary structures is required. The variation in structure (straight in some cases, braided in others, kinked in one case) requires explanation. All but one of the filaments is perpendicular to the Galactic plane.
4. *Location*. A good model has to account for the numerous filaments in the Galactic centre region and their apparent association with star formation regions and molecular clouds — together with the absence of filaments associated with such regions outside of the Galactic centre.

2.2.1 Star-based Models

Nicholls & Le Strange (1995) proposed a model for the Snake in which a star trail caused by a rapid runaway star

opened up a conduit in the ISM. This model was discussed fully by Gray et al. (1995).

Rosner & Bodo (1996) proposed that the source of relativistic electrons is the terminal bow shock of the wind from a massive star, or cluster of stars. The electrons are transported away from the shock in the direction of the local interstellar magnetic field. This creates a flux tube whose lateral extent $\sim$ pc is determined by the size of the stellar wind bubble and which is loaded by relativistic electrons from the wind shock. The synchrotron cooling from relativistic electrons generates a cooling instability and this causes the flux tube to contract laterally generating a magnetic field about 30 times larger.

This model does not seem to have much observational support. For example there is no evidence for massive stars at any of the radio-bright regions of the various filaments, although such stars are difficult to detect in the near IR because of their blue colours and the lack of strong spectral features (McGregor, private communication). Perhaps more importantly, the existence of a synchrotron cooling instability is problematical. The pressure in a conventional non-thermal plasma with electron spectral index greater than two is dominated by the lowest energy particles and the cooling is dominated by the highest energy particles so that cooling does not greatly affect the pressure, rendering collapse through cooling difficult. A let-out here is that the flat spectral index of the synchrotron emission may indicate a flat electron distribution in which the pressure, as well as the radiation, is dominated by the highest energies. However, the spectral index along many filaments is a function of position and this is not taken into account in the model.

2.2.2 Interaction of a Galactic Wind with Molecular Clouds

Shore & LaRosa (1999) invoked the interaction of a magnetised galactic wind with molecular clouds as the origin of the filaments. In their theory the filaments are analogous to cometary tails. The magnetic field in the wind ‘wraps around’ the molecular cloud forming a current sheet in its wake. The lateral size of the filament is of the order of the size of the molecular cloud and the field is amplified by stretching in the wake until it reaches equilibrium with the ram pressure of the wind. Stochastic turbulence generated by the unstable current sheet is invoked as the mechanism for particle acceleration. In their theory, the ultimate source of energy is the total magnetic energy in the wake. However, there is no physical description as to how this source of energy is coupled to the turbulence. Normally, in a turbulent cascade, the dissipated power is related to the energy in large scale eddies. For many of the filaments, one can make a case for the general physical morphology proposed by Shore & LaRosa (1999). In the Yusef-Zadeh, Morris, & Chance (1984) arcs, for example, there are molecular clouds associated with radio-bright regions. However, in the Snake, there are no molecular clouds at the bright spots that are coincident with the kinks. The general direction of filaments approximately

perpendicular to the Galactic plane is consistent with this model. However, the discovery of two systems of filaments parallel to the galactic plane (Lang et al. 1999; LaRosa, Lazio, & Kassim 2001) seems to contradict it.

2.2.3 Cloud–Magnetic Field Interactions

Serabyn and Morris and their colleagues have been responsible for much of the detailed observational work of the non-thermal and molecular regions in the vicinity of the Galactic centre. In the course of this observational program Serabyn & Morris (1994) have proposed an interesting explanation for the first set of Galactic centre filaments observed — the Arc. Their model involves the interaction of a fast-moving molecular cloud with an ambient mG magnetic field. The leading face of the cloud is ionised by radiation from the nearby HII region, and the turbulent interaction of the face with the mG interstellar magnetic field leads to reconnection and acceleration of monoenergetic relativistic electrons. These stream away from the face of the cloud at the Alfvén speed. The estimate of $B \sim \text{mG}$ stems from the equilibration of turbulent and magnetic pressure in the clouds. They argue that this magnetic field must be characteristic of the entire region and not localised to the cloud for otherwise the filaments would expand laterally outside of the molecular clouds which do not fill the arc region but instead are clumped inside it. Whether one accepts this part of the theory or not, and we discuss this further in Section 3 below, Serabyn & Morris (1994) present good arguments that the relativistic electrons are the consequence of the cloud–magnetic field interaction since the onset of radio emission in each filament is at the edge of the molecular clouds. As they point out, this could indicate either emission or absorption by the molecular structure. However, they suggest that the increase in disorder of the non-thermal filaments away from the clouds leading to plume-like structures at some distance from the Galactic plane and the steepening of the spectral index with distance from the Galactic plane both indicate that the non-thermal particles originate near the molecular/ISM interface. These plumes may be a key indicator of the dynamics of the Arc and surrounding structures and are clearly evident in the LaRosa et al. (2000) image.

The spectrum of these particular non-thermal filaments, described by $F_\nu \propto \nu^{0.3}$, suggested to Serabyn & Morris (1994) a monoenergetic electron spectrum with the electrons accelerated by electrostatic fields in the reconnection region. However, such a spectral index is also characteristic of synchrotron emission from an arbitrary distribution, at frequencies lower than that corresponding to the low energy cutoff. In either case, the monoenergetic or minimum Lorentz factor $\gtrsim 500$ corresponds approximately to 0.25 GeV. Whether the spectrum is monoenergetic or something more complicated, Serabyn & Morris (1994) note that acceleration to such energies using Petschek reconnection would occur over about $10^{14} \text{ cm} \sim 0.8$ mas given that particles stream out of the reconnection zone at the Alfvén speed. Thus, VLBI observations could

possibly resolve the reconnection region given enough sensitivity.

Pohl, Reich, & Schlickeiser (1992) have also modelled the radio emission from the southern plume that seems to be connected to the Arc. The observational data indicate a decreasing spectral index along the plume and they have modelled this reasonably successfully using a steady state model which incorporates the injection of monoenergetic electrons, their cooling due to synchrotron and inverse Compton emission, and their diffusion due to scattering. The calculated synchrotron emission takes account of the widening flux tube. This model has much in common with the model that we have proposed for the Snake, except that theirs is a steady state model and ours is time dependent, both of these approaches being appropriate to the given circumstances. An interesting point of consistency is their value for the diffusion coefficient $\sim (2.4\text{--}10) \times 10^{25} \text{ cm}^2 \text{ s}^{-1}$ (see Section 4.6). It would be interesting to revisit the Pohl, Reich, & Schlickeiser (1992) model and investigate the effect of more general electron spectra.

2.2.4 Electrodynamic Models

Conventional MHD models. Heyvaerts, Norman, & Pudritz (1988) attempted to explain the Yusef-Zadeh, Morris, & Chance (1984) Arc by postulating the ejection of coronal loops at speeds $\sim 1000 \text{ km s}^{-1}$ from the black hole at the Galactic centre. These were then supposed to interact with dense gas in the vicinity of Sagittarius A producing the Arc via reconnection processes. This idea was criticised by Morris & Yusef-Zadeh (1989) on the basis of fine-tuning: compared to the travel time of the loops from the black hole, the interaction time is relatively small. It was also criticised by Benford (1988) on the basis of requiring a special viewing angle and there being no comparable interaction on the opposite side of the Galactic centre.

Our own theory for the Snake (Bicknell & Li 2001) also falls into the class of conventional MHD models. This is discussed in more detail below.

Unconventional models. In conventional MHD one calculates the electric current from the curl of the magnetic field whose evolution is either described by the flux-freezing approximation or by a description that incorporates diffusive processes, e.g. reconnection. Benford (1988, 1997), on the other hand, motivated by his research in laboratory plasmas, has focused on the current in a theory for the Arc and the Snake. In his theory, an electric field $\mathbf{E} = c^{-1}(\mathbf{v}_c \times \mathbf{B})$ is produced by the interaction of a conducting cloud of velocity $\mathbf{v}_c$ with the pre-existing magnetic field, $\mathbf{B}$, whose magnitude is of the order of a mG. In the boundary layer at the edge of the cloud, the current and electric field are perpendicular to the magnetic field but then link up with the magnetic field outside the cloud. A current circuit is formed with the current parallel to the field outside the cloud and, in addition, a return current is established in the ISM. In the case of the Arc he suggests that the current may return from the plume-like ends of the Arc and find its way through the ISM in the

vicinity of the Galactic centre or may link up with other filaments south of the Galactic plane. The resistance of the circuit, resulting from scattering of the electrons by ion acoustic turbulence generated in the current loop, is a key element of the theory. In his theory for the Arc, the joule dissipation due to this resistance is the energy source for particle acceleration and the resultant radio emission.

The current generates a toroidal field. In the case of the Arc, Benford estimates a small radius $\sim 10^9$ cm per current filament, requiring congregation of filaments to form discernible structures and predicting that the observed filaments should break up into smaller subfilaments at higher resolution. In Benford (1997), in which the earlier ideas developed for the Arc are applied to the Snake, the same battery mechanism is invoked and the development of the toroidal field leads to pinched current loops. Using classical results relating to the relative importance of the pinch and kink instabilities, Benford argues that the kink instability dominates when $B_\phi \sim B_z$, explaining the kinks in the Snake. In addition, these are invoked as the site of primary resistance and dissipation. However, the discussion of filamentation is different. Benford appeals to a filamentary instability identified by Molvig (1975). This requires a minimum flow speed in the pinched current defined by $v/c > 3 \times 10^{-2} (B/\text{mG}) n_p^{-1} (2f - 1)^{-1/2}$ where $f = I_r/I_z$ is the ratio of the radial to axial currents. The minimum velocity requires electrons that are moving at much greater than the drift speed required to maintain the magnetic field and necessarily involves the particles that are accelerated by the dissipation. However, the minimum velocity also exceeds the Alfvén speed but the effect of resonant scattering is ignored. Moreover, no reason is given as to why the current propagates over the distance to the kinks without dissipation or for the *distribution* of radio flux density and spectral index in the vicinity of the kinks. Furthermore, the ambient magnetic field $\sim 7 \mu\text{G}$ deduced by Gray et al. (1995) from a sound analysis of their rotation measure data argues strongly against a pervasive magnetic field $\sim \text{mG}$ in this part of the Galactic centre. To put it another way, if one wants to argue for a mG field in this region then one has to show why the Gray et al. (1995) rotation measure analysis is wrong.

Shock waves, morphologically unusual SNRs, and exotica. You are referred to Gray et al. (1995) for a discussion of these.

3 Estimates of the Magnetic Field in the Galactic Centre

As we have seen, the numerous theories for the filaments in the Galactic centre involve various assumptions for the magnetic field — with many theories postulating an interstellar magnetic field of the order of a milligauss. Other theories invoke a more modest magnetic field that is enhanced in some way. Hence, it is a good idea to address this issue separately and to ask what evidence there is for a large scale milligauss magnetic field and if there are other alternatives.

A convenient starting point for the discussion of these assumptions entails consideration of the *minimum energy* estimates of the magnetic flux density in the Galactic centre filaments. These estimates are generally of the order of a mG and, of course, are always subject to the usual challenge: how do you know that the filaments are in a minimum energy state? The magnetic field could be much higher or lower. This is correct. However, such calculations do reveal that the *minimum pressure* of the filaments $\sim 10^{-8} \text{ dyn cm}^{-2}$ is higher than the normal value $\sim 10^{-12} \text{ dyn cm}^{-2}$ for the ISM so that one is presented with two choices: (1) The Galactic centre ISM has a high total (magnetic plus thermal) pressure that confines the filaments, consistent with the notion of a $\sim \text{mG}$ poloidal field (Serabyn & Morris 1994; Morris 1998; Chandran, Cowley, & Morris 2000). (2) The filaments are self-confined, i.e. they are in an almost force-free configuration with a toroidal field $B_\phi \gtrsim B_z$, where B_z is the field along the filament. The little-noted but extremely important observational deduction from Faraday rotation measurements (Gray et al. 1995) that the magnetic field in the vicinity of the Snake $\sim 7 \mu\text{G}$ tends to rule out a large poloidal field and therefore the second choice becomes a real possibility. To put it another way, if one wishes to postulate a milligauss magnetic field then one has to show how the analysis of Gray et al. (1995) can be plausibly altered or perhaps why it only applies to the immediate vicinity of the Snake.

On the other hand, Serabyn & Morris (1994) have, by equating the turbulent and magnetic pressures in the molecular clouds associated with the arc, argued for a strong magnetic field in the vicinity of Sagittarius A. (For a refinement of these calculations, see Morris & Serabyn (1996).) Certainly the visual impression created by the Arc and the Threads (see, for example, the image in Morris & Serabyn (1996)) conveys the impression of a large scale poloidal field illuminated in places by relativistic electrons. Nevertheless, at this point we draw attention to another feature of the observations, namely the existence of faint, apparently *helical* emission features projected on the linear filaments of the Arc (Yusef-Zadeh & Morris 1987; Anantharamaiah et al. 1991). Apart from the paper (Yusef-Zadeh & Morris 1987) which documented the discovery of this feature, little comment has been made on this observation. However, such helical features are the ‘smoking gun’ for a force-free field since a helix is the natural force-free configuration and the dynamics of force-free fields could well be the key to the entire phenomenon of filaments in the Galaxy. Indeed, Yusef-Zadeh & Morris (1987) offered the suggestion that reconnection, occurring between force-free flux tubes of opposite polarity, could account for the energetics of the Arc. They also speculated that the northern and southern plumes into which the Arc degenerates may be the result of weakening confining pressure. Given the variety of solar coronal magnetic activity that takes place in a force-free environment, the scenario considered by Yusef-Zadeh & Morris (1987) is surely one of many and

this could well be a rich source of theoretical work in the future.

If the vicinity of the Arc is indeed a force-free region, then the Arc would represent the milligauss central region of a more extended structure, possibly formed by the rotation of footpoints in the Galactic plane. (Yusef-Zadeh & Morris (1987) had suggested that the flux tubes associated with the Arc are anchored in the Galactic halo.) If the field in the various regions of the Galactic centre, associated with the filaments, is indeed force-free, then this weakens the case for a pervasive large scale milligauss field.

It is also apposite to mention here the estimates of magnetic fields in other regions of the Galactic centre where the emission is thermal rather than non-thermal. For example, Killeen, Lo, & Crutcher (1992) and Plante & Crutcher (1999) detected fields of 2–3 mG in the circumnuclear disk. For a summary of other magnetic field estimates in the Galactic centre see Roberts (1999). All of these observations relate to dense regions of the Galactic centre so that it is possible that the measurements are not indicative of the tenuous gas.

If there is a large milligauss field in the Galactic centre, what is its origin? Advocates of a large magnetic field appeal to Sofue & Fujimoto (1987) who outlined how magnetic field may accumulate in the Galactic centre through diffusion from scales ~ 10 kpc. A significant poloidal field is produced because the initial field is primordial. Such a scenario involves untested assumptions about the nature of galaxy formation and evolution. However, no detailed models or numerical simulations have been carried out based upon it. Another possibility is the combined dynamo mechanism that is mediated by an activity driven outflow from the nucleus proposed by Lesch et al. (1989).

4 A Theory for the Filament, the Snake, Involving a Reconnecting Coil

4.1 Overview

In our own initial attempt to unravel the mystery posed by the existence of the numerous Galactic centre filaments, we decided to concentrate on the Snake. The comprehensive observational program and the analysis of the VLA and ATCA data reported by Gray et al. (1995) makes detailed theoretical analysis and model fitting possible. It is possible that the main features of our model that we propose may be relevant to the other filaments and, possibly, the future incorporation of other processes (in particular synchrotron cooling and distributed acceleration sites) may lead to further advances of the entire Galactic centre filamentary phenomenon.

A key feature of the Snake is that its flux density is closely associated with ‘kinks’ in its structure. The flux density has local maxima at a ‘major kink’ and at a ‘minor kink’. Moreover, the spectral index, α , decreases (i.e. becomes flatter) away from the major kink, highlighting the potential dynamical importance of the kinks in explaining the dynamics of the Snake. Our model fits into the class of models involving conventional electrodynamics and does not invoke a large poloidal magnetic field pervading the Galactic centre region.

It was the association of features in the radio emission with the kinks that motivated us to think in terms of a dynamical theory for the emission that involved the classical kink instability of a twisted magnetic flux tube. The elements of our theory are depicted schematically in Figure 1 and can be summarised as follows:

1. The Snake is a large (~ 60 pc) magnetic flux tube, with the field lines anchored in a rotating molecular cloud and in some other region of the ISM that may or may

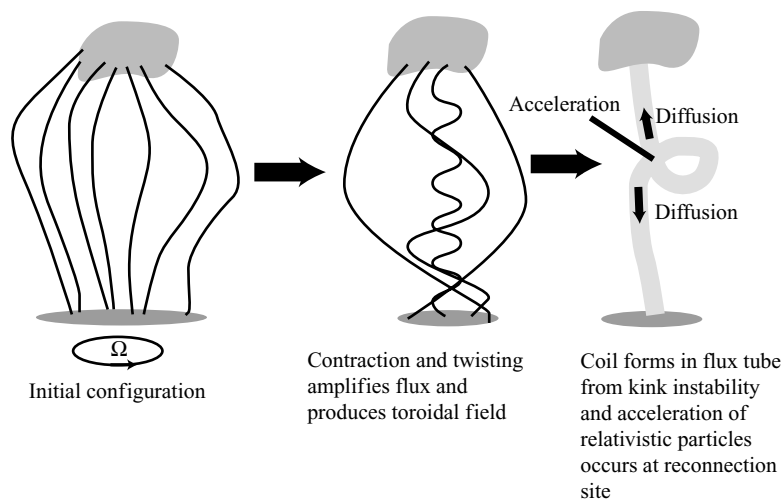


Figure 1 A schematic indication of the dynamical development of a force-free flux tube that has one end anchored in a rotating and contracting molecular cloud and the other end anchored in another part of the ISM.

not rotate significantly. Initially (i.e. before significant contraction), the field lines diverge from the molecular cloud forming part of the network of magnetic field lines in the Galactic centre.

2. As the cloud contracts, the field increases in the centre of the cloud and reaches a value $\sim \text{mG}$ typical of molecular cloud cores (Roberts 1999).
3. At the same time, the continual twisting of the field leads to a toroidal field, B_ϕ , that is of the order of B_z and which draws the central field lines into a thin flux tube. That is, the flux tube becomes self-collimated and force-free.
4. Furthermore, when $B_\phi \sim B_z$, the flux tube is unstable to the kink instability — as in the model of Benford (1997). This instability leads to the formation of local loops, or coils, in the flux tube, much like the twisting of a rubber band leads to knots along its length.
5. The coils dissipate magnetic energy as a result of reconnection and possibly associated shocks. This leads to the acceleration of relativistic particles.
6. The relativistic electrons (and, of course, the other fast particles) diffuse away from the kink resulting in a spread of radio intensity with distance away from the kink.
7. The diffusion is energy dependent. The highest energy particles diffuse the fastest so that the spectral index flattens with distance from the kink.

Our theory differs from that of Benford (1997) in that the kink is produced by conventional MHD processes, rather than by an externally induced current. It has one feature in common, namely the production of the kink instability when $B_\phi \sim B_z$. However, the mechanism for the production of the toroidal field is quite different. Also note that the mechanisms for the production of force-free magnetic fields in the Galactic centre is a topic that is in its infancy. Our own suggestion involving rotating molecular clouds may be one of many and the major part of our model concerns the effect on the radio surface brightness once the toroidal field increases to the point where the flux tube becomes kink-unstable.

4.2 Acceleration and Diffusion of Particles

We model the Snake as a straight flux tube with spatially constant cross-sectional area and magnetic flux density. Let $f(p, x, t)$ be the phase-space density of electrons, at time t and at distance x from a reconnecting kink, located at $x = 0$; let $K(p)$ be the spatial diffusion coefficient for electrons, and $C(p)$ be the creation rate of particles per unit volume of the flux tube, per unit volume of momentum space. We then describe the acceleration and diffusion of particles along this tube by the following equation:

$$\frac{\partial f(p, x, t)}{\partial t} - \frac{\partial}{\partial x} \left[K(p) \frac{\partial f(p, x, t)}{\partial x} \right] = C(p) \delta(x). \quad (1)$$

The delta function indicates that we treat the coil as a relatively small section of the entire length of the tube. The boundary condition to this diffusion equation derived

by integrating this equation across $x = 0$ is

$$\left. \frac{\partial f}{\partial x} \right|_{x=0} = -\frac{1}{2} \frac{C(p)}{K(p)}. \quad (2)$$

Throughout the period of an outburst, we assume that the injection rate, $C(p)$ is constant and that

$$C(p) = C_0 \left(\frac{p}{p_0} \right)^{-s} \quad (3)$$

where $p_0 = \text{GeV}/c$ is the fiducial value of the momentum used throughout this treatment. In adopting this description, the details of the injection process are not considered. A power law with $s \approx 4$ is relevant if strong shocks are involved.

We take the diffusion parameter also to be described by a power law

$$K(p) = K_0 \left(\frac{p}{p_0} \right)^\beta. \quad (4)$$

This dependence of the diffusion coefficient on momentum is crucial. A positive value of β implies that high energy electrons diffuse the fastest and thus dominate the radio emission at large distances from the site of injection. This is our explanation for the flattening spectral index away from the kink.

In this model, we have ignored synchrotron losses of the diffusing particles. This is justified *a priori* by the absence of any features in the spectrum of the Snake that could be ascribed to radiative losses. We return to this point below in Section 4.6

4.3 Parameters and Solution of the Diffusion Equation

The diffusion equation is expressed in dimensionless form using a scaling length, L , that is also used to define a dimensionless time variable. We have

$$\xi = \frac{x}{L}, \quad (5)$$

$$\tau = \frac{K(p)t}{L^2} = \frac{K_0 t}{L^2} \left(\frac{p}{p_0} \right)^\beta, \quad (6)$$

$$g(\xi, \tau) = \frac{2K_0}{C_0 L} \left(\frac{p}{p_0} \right)^{s+\beta} f(p, x, t). \quad (7)$$

In these variables the diffusion equation and boundary condition take a particularly simple form which has an analytical solution (see Bicknell & Li 2001). The number of electrons per unit Lorentz factor is $N(\gamma, \xi, \tau) = N_0 \gamma^{-a} g(\xi, \tau)$, where $N_0 = 2\pi (m_e c)^3 (C_0 L / K_0) \gamma_0^{2+a}$ and $a = s + \beta - 2$. The angle-averaged synchrotron emissivity may be estimated from $N(\gamma, \xi, \tau)$ using the angle-averaged single-electron synchrotron emissivity, $\bar{F}(y)$, defined by

$$\bar{F}(y) = y \int_y^\infty \sqrt{1 - y^2/u^2} K_{5/3}(u) du \quad (8)$$

with $K_{5/3}(u)$ the usual modified spherical Bessel function of order $5/3$.

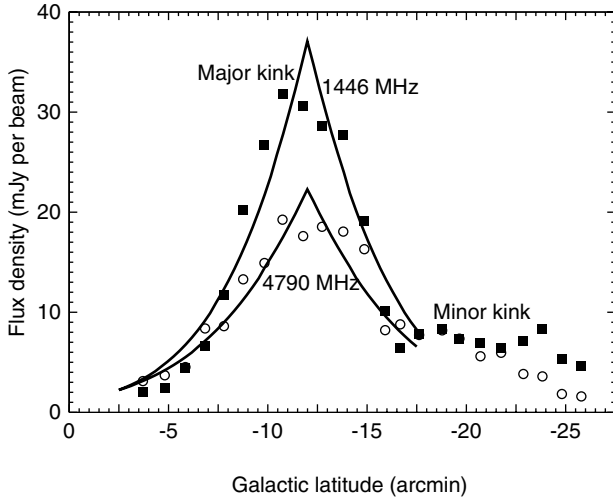


Figure 2 Model fit to the data of Gray et al. (1995). The fit is restricted to the region around the major kink in order to avoid additional parameters describing the minor kink region as well.

4.4 Fit to the Data

The emissivity is used to calculate the flux density per beam along the Snake (again see Bicknell & Li (2001) for the details), and we can then use that flux density to fit the observational data, solving for the parameters, N_0 , $\tau_0 = K_0 t / L^2$, B , β , and a . We fitted that section of the data most clearly related to the major kink in order to avoid introducing additional parameters (see Figure 2). Although there are 30 data points in this region, data at lower and higher frequencies would be useful in further constraining the model and/or evaluating its predictions.

The parameters of this fit are

$$\begin{aligned} N_0 &= 3.5 \times 10^{-5} \text{ cm}^{-3} & B &= 0.37 \text{ mG} & \beta &= 0.57 \\ a &= 2.14 \Rightarrow s = 3.57 & \tau_0 &= K_0 t / L^2 = 0.46. \end{aligned} \quad (9)$$

The magnetic field is constrained by the data, albeit not very strongly, because the energy spectrum of the emitting electrons is controlled by the diffusion and the magnetic field affects the way in which this is reflected in the frequency domain.

There are some interesting features of the fit:

- The magnetic field is much higher than Gray et al. (1995) inferred for the ISM in the vicinity of the Snake. This is an additional argument for the Snake flux tube being force-free.
- The value of s , the momentum index of the creation rate of relativistic electrons, is reasonably close to the canonical value of 4 for shocks in a thermal medium (Blandford & Ostriker 1978).
- The value of β is close to the model values derived for the propagation of cosmic rays in the ISM of the Galaxy. For example, Ormes & Protheroe (1983) derived a value of $\beta = 0.8$; more recently Webber, Lee, & Gupta (1992) derived a value of $\beta = 0.6$. Future models may be required to concentrate on the effects

of ‘minimal acceleration’ (Ptuskin et al. 1999) and the effects of synchrotron cooling, the latter becoming important at higher frequencies. Nevertheless, the agreement between our estimation of β and its value using a similar propagation model in an entirely different context give us confidence that the model should be taken seriously.

- The dimensionless time τ_0 does not have a special value, e.g. $\tau_0 = 10^{-3}$ or $\tau_0 = 10^6$, indicating that the model is not ‘fine-tuned’.

4.5 The Energy Budget

The energy budget is an important constraint on any dynamical process. In this case, the energy available from the annihilation of magnetic field must exceed the inferred energy in relativistic electrons. Because of the electron spectral index, one has to invoke a high energy cutoff (E_c) in order to evaluate the energy. Using the parameters of the model, the total energy of relativistic electrons in the tube is

$$\begin{aligned} E_e &= 6.3 \times 10^{44} \left(\frac{E_c}{\text{GeV}} \right)^{0.43} \\ &= 3.9 \times 10^{45} \text{ ergs} \quad \text{for } E_c = 10 \text{ GeV} \\ &= 1.1 \times 10^{46} \text{ ergs} \quad \text{for } E_c = 100 \text{ GeV}. \end{aligned} \quad (10)$$

The magnetic energy stored in the coil $E_m \approx 3.5 \times 10^{46}$ ergs. This exceeds the energy in relativistic electrons, comfortably in the case of a 10 GeV cutoff.

4.6 Timescales

It is important to reconcile the various timescales that are either directly or indirectly related to the model. We did not discuss the synchrotron cooling timescale in our ApJ letter. However, this is an important point and we discuss it in detail here.

1. Since the processes of twisting and kinking of the flux tube are related to the magnetic field the relevant dynamical timescale is the Alfvén time, $t_A = L_{\text{tube}} / v_A$, where L_{tube} is the length of the tube and $v_A = B / (4\pi \mu n m_p)^{1/2}$ is the Alfvén speed. Scaling to the visible length of the Snake, $t_A \approx 1.7 \times 10^5 (L_{\text{tube}} / 60 \text{ pc}) (B / 0.4 \text{ mG})^{-1} (n / 10 \text{ cm}^{-3})^{-1/2} \text{ yr}$. (The fiducial value of $n = 10 \text{ cm}^{-3}$ is based upon the estimate of $n \sim 7\text{--}14 \text{ cm}^{-3}$ (Gray et al. 1995) for the ambient ISM ionised density, derived from rotation measure variations.)
2. According to Amo et al. (1995) and Bazdenkov & Sato (1998) a reconnecting coil disappears ‘explosively’ in 1–3 Alfvén times, i.e. approximately every $t_{\text{burst}} \approx (1.7\text{--}5.0) \times 10^5 (L_{\text{tube}} / 60 \text{ pc}) (B / 0.4 \text{ mG})^{-1} (n / 10 \text{ cm}^{-3})^{1/2} \text{ yr}$.
3. Explosive bursts recur approximately every 5 Alfvén times, i.e. on a timescale $t_{\text{recur}} \approx 7.5 \times 10^5 (L_{\text{tube}} / 60 \text{ pc}) (B / 0.4 \text{ mG})^{-1} (n / 10 \text{ cm}^{-3})^{1/2} \text{ yr}$.
4. The time for which the electrons have been diffusing is $t_{\text{diff}} = L^2 K_0^{-1} \tau_0 \approx 3.1 \times 10^5 K_{0,26}^{-1} \text{ yr}$, where

$10^{26} K_{0,26} \text{ cm}^2 \text{ s}^{-1}$ is the value of the diffusion parameter for GeV electrons.

5. Synchrotron cooling has not been directly incorporated into our model for the reason given above. However, for consistency, the absence of synchrotron cooling features should be consistent with the estimate of the magnetic field. The synchrotron cooling time is $t_{\text{syn}} \approx 7.8 \times 10^4 (B/0.4 \text{ mG})^{-3/2} (\nu/5 \text{ GHz})^{-1/2} \text{ yr}$.

Validity of the model requires that the diffusive timescale be less than both the burst timescale and the synchrotron cooling timescale. Moreover, the diffusive timescale should not be too much less than the burst timescale, since that would imply that we are observing the Snake at a special epoch in its history. These constraints can be satisfied for reasonable parameters. For example, for $L_{\text{tube}} \approx 60 \text{ pc}$, $n = 10 \text{ cm}^{-3}$, and a burst lasting $3t_A$,

$$\begin{aligned} t_{\text{diff}} < t_{\text{burst}} &\Rightarrow K_{0,26} \left(\frac{B}{0.4 \text{ mG}} \right)^{-1} > 0.62 \\ t_{\text{diff}} < t_{\text{syn}} &\Rightarrow K_{0,26} \left(\frac{B}{0.4 \text{ mG}} \right)^{-3/2} > 3.97. \end{aligned} \quad (11)$$

We could allow *some* variation in the magnetic field since this is not well determined by the model. However, even fixing B at 0.4 mG , these constraints are satisfied for $K_{0,26} > 4$, implying that $t_{\text{diff}}/t_{\text{burst}} \lesssim 0.16$. If only a small variation in B is allowed, e.g. $B = 0.2 \text{ mG}$, then $K_{0,26} > 1.4$ and $t_{\text{diff}}/t_{\text{burst}} \lesssim 0.9$. Both of these ratios of $t_{\text{diff}}/t_{\text{burst}}$ are acceptable. Note, however, that we would not wish K_0 to be arbitrarily high. The diffusion timescale would then become quite short compared to the burst timescale. Therefore, we adopt $K_{0,26} \sim 1\text{--}10$ as a working hypothesis.

The consideration of the synchrotron timescale suggests an explanation for the difference between flat spectrum filaments such as the Snake and the other steep spectrum filaments. We suggest that the other filaments are older in terms of synchrotron age; their spectra may have gone through a similar stage to that of the Snake but have since steepened. The parameters that determine this are the magnetic field and the age of the filament so that a more general model, with allowance for synchrotron cooling, should show that the ratio of the age to the synchrotron cooling time is larger than in the Snake.

An appealing aspect of the above timescales is that the recurrence time of the bursts is such that it would not be surprising to see one burst fading whilst another is bright. Thus our explanation for the minor kink is that it represents a previous outburst that has substantially, but not completely, faded.

4.7 Resonant Scattering

This is an area of this research in which we relied very heavily on the theoretical results on the scattering of fast particles in Don Melrose’s two-volume work on plasma astrophysics (Melrose 1982).

In order to estimate the physical time for which the present outburst has been in existence, it is necessary

to estimate the diffusion parameter, $K(p)$. We invoke a spectrum of resonant waves in which the energy per unit wave number, $W(k)$, is given by

$$W(k) = W_0 \left(\frac{k}{k_0} \right)^{-\eta} \quad (12)$$

where k_0 is the resonant wave number eB/cp_0 corresponding to $p_0 = \text{GeV}/c$. Let the total wave energy density be W_m , then using formulae given in Melrose (1982), the diffusion parameter, corresponding to $W(k)$, is

$$\begin{aligned} K(p) &= 1.4 \times 10^{19} \eta(\eta + 2) \left(\frac{B}{\text{mG}} \right)^{-1} \\ &\times \left(\frac{k_0 W_0}{W_m} \right)^{-1} \left(\frac{p}{p_0} \right)^{2-\eta}. \end{aligned} \quad (13)$$

Our value of $\beta \approx 0.6$ implies that $\eta \approx 1.4$. This is not the index of $5/3$ that one expects from Kolmogorov turbulence. However, it is close to the index of 1.5 that one expects from turbulence in a plasma in which the turbulent magnetic energy is comparable to the turbulent hydro-magnetic energy (Kraichnan 1965). (See Ruzmaikin, Shukurov, & Sokoloff 1987, p. 142 ff., for a description of the differences between hydrodynamic and magnetic turbulence.)

For the ISM, cosmic ray physicists generally assume $K_0 \sim 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (e.g. Ptuskin et al. 1999), implying $k_0 W_0 / W_m \sim 2 \times 10^{-6}$ for $B \sim 3 \mu\text{G}$. If the *relative* level of turbulence (expressed by the ratio $k_0 W_0 / W_m$) in the Snake filament is similar to that in the general ISM, then a magnetic field a factor of 100 times larger gives a value of K_0 a factor of 100 times smaller, as required. Why the relative level of turbulence should behave in this way is presumably related to the length and velocity scales of turbulence in the ISM which we shall not go into here. However, it is clear that the dependence of $K(p)$ upon the magnetic field is important, and in our view, is the major reason for the reduced rate of diffusion in the Snake. As we have noted above, Pohl, Reich, & Schlickeiser (1992) derived a diffusion coefficient $\sim (2.4\text{--}10) \times 10^{25} \text{ cm}^2 \text{ s}^{-1}$ for their model of the southern plume for a magnetic field 2.5 times higher than we have estimated for the Snake. These estimates are consistent with the same relative level of turbulence and $K_0 \propto B^{-1}$.

5 The Origin of the Magnetic Field in the Snake

In our model, the magnetic flux tube originates in the cores of molecular clouds, and as we have pointed out, this is consistent with the estimated strengths of the magnetic fields in the Galactic centre filaments being of the order of the strengths of the magnetic field in molecular cloud cores. Uchida et al. (1996), in fact, discovered a molecular cloud–HII region complex at the northern end of the Snake, near the Galactic plane. The formation of stars in such clouds is complex and may be mediated by magnetic fields and turbulence which determine the way in which a molecular cloud or sub-regions contract to the star forming stage. A comprehensive description of how our model

for the Snake fits into theories for star formation and the contraction phase of molecular clouds is beyond the scope of this paper. Nevertheless, we can at this stage indicate how a magnetic flux tube may become twisted and indicate the magnitude of angular velocity required.

In Bicknell & Li (2001), we mentioned two possible regimes of magnetically dominated star formation that have dominated research in this field for some time: sub-critical and supercritical collapse. In the former case, the cloud is initially supported by the magnetic field and subsequently ambipolar diffusion allows the cloud to contract (e.g. Basu & Mouschovias 1995a, and references therein). In the latter case, the cloud is not initially supported by the magnetic field and contracts, conserving angular momentum, until it comes to a state of centrifugal equilibrium. Thereafter, magnetic braking becomes important and further contraction is mediated by the radiation of torsional Alfvén waves along the magnetic field (e.g. Mestel & Paris 1984; Mestel 1999, and references therein). Supercritical collapse would seem to be the most favourable regime for the scenario of filament formation that we have outlined.

However, more recently, various workers (e.g. Ballesteros-Paredes, Vázquez-Semadeni, & Scalo 1999; Padoan & Nordlund 1999; Heitsch, Mac Low, & Klessen 2001, and references therein) have turned to consider more the physics of cloud collapse/contraction in a turbulent magnetised medium with the magnetostatic field playing a less important role. Moreover, the existence of distinct clouds in the ISM is superseded by the view that the observed clouds are essentially density inhomogeneities in a turbulent gas with a continuous velocity field linking the various regions. In this case, the linkage between twisting of magnetic fields and star formation is less clear, although this current work tends to favour the supercritical regime, but in a way that is more complex than envisaged by Mestel & Paris (1984). Also note that if the field in the Galactic centre is as high as a milligauss, then the effects of magnetostatic fields cannot be ignored. *Inter alia*, this may make the clouds more long-lived.

Most of the simulation work on contracting molecular clouds has been done with zero or small initial angular velocity. The typical initial angular velocity possessed by a cloud forming from a smooth medium is one half the curl of the smooth velocity field. For this reason, Basu & Mouschovias (1995b) began their simulations with an angular velocity $\omega \sim 10^{-15} \text{ s}^{-1}$. The initial value of the angular velocity is important for the twisting of magnetic flux tubes; if it were significantly higher than $\sim 10^{-15} \text{ s}^{-1}$ then rapidly rotating cores could develop. The special character of the Galactic centre may be important in this regard. If we estimate the circular velocity field to be constant and approximately 200 m s^{-1} from $\sqrt{2}$ times the velocity dispersion of $\sim 125 \text{ km s}^{-1}$ (see Saha, Bicknell, & McGregor 1996) the local angular velocity $\approx 2 \times 10^{-14} \text{ s}^{-1}$ – 20 times the Basu and Mouschovias value. Moreover, the CO longitude–velocity diagram of the inner 300 pc of the Galaxy (Brown & Liszt 1984) shows complex structure and a high velocity dispersion

so that it is feasible that molecular clouds within this environment would collide, generating shocks that in turn can generate a large amount of vorticity (Binney 1974). There is one intriguing piece of evidence for rapidly rotating molecular gas in the Galactic centre. The cloud CS1W associated with the Arc exhibits a velocity gradient of $17 \text{ km s}^{-1} \text{ pc}^{-1} \approx 5.5 \times 10^{-13} \text{ s}^{-1}$ (Serabyn & Morris 1994).

Given that star formation in contracting magnetised molecular clouds is a complex process that currently is not well understood, especially in the complex flow-field of the Galactic centre, the best that we can do is indicate the magnitude of angular velocity that is required and indicate some of the physics and rotation velocities that are relevant to the formation of twisted magnetic flux tubes. In the following we have in mind a scenario involving supercritical contraction and magnetic braking.

The twisting of a flux tube is linked to the radiation of angular momentum from the rotating cloud. The flux of angular momentum, dJ/dt , through a flux tube of radius R is given by the expression

$$\frac{dJ}{dt} = 2\pi \int_0^R \frac{r B_\phi B_z}{4\pi} r dr. \quad (14)$$

The toroidal field is crucial for magnetic braking. In the standard case, where the field lines are open to infinity, the angular momentum is radiated via torsional Alfvén waves (see Mestel 1999, p. 452). Let ρ_0 be the ambient density and Ω_0 the angular velocity of the cloud. The toroidal field produced in the flux tube is given by

$$B_\phi = -r(4\pi\rho_0)^{1/2}\Omega_0 \approx 1.5 \times 10^{-6} \left(\frac{n}{10 \text{ cm}^{-3}} \right)^{1/2} \times \left(\frac{\Omega_0}{\text{km s}^{-1} \text{ pc}^{-1}} \right) \text{ gauss}. \quad (15)$$

Development of a toroidal field with a magnitude $\sim 4 \times 10^{-4} \text{ G}$ requires an angular velocity $\sim 270 \text{ km s}^{-1} \text{ pc}^{-1}$. In the context of the molecular clouds in the ISM of the Galaxy, this is huge!

If, on the other hand, the field is anchored in another region along the flux tube, then the corresponding solution for the toroidal field is

$$B_\phi = -\frac{r\Omega_0 B_0 t}{L_{\text{tube}}}. \quad (16)$$

This solution for B_ϕ can be derived by elementary means by considering the twisting of field lines in a tube that is slowly rotated (Alfvén 1950). It can also be derived from the equations for torsional Alfvén waves (see Bicknell & Li 2001). This solution is the simplest that one can consider in the current context. It does not take into account the contraction of the cloud, nor the initial divergence of the field lines issuing from it. Nevertheless, it is of interest to compare this solution with that for a tube anchored at one end only. The tube approaches its unstable configuration when $B_\phi \sim B_0$, i.e. when $t \sim L_{\text{tube}}/\Omega_0$. If we consider 10^7 yr as the maximum lifetime of a molecular cloud,

then a twisted tube with $L_{\text{tube}} \sim 60$ pc and $r \sim 0.2$ pc will become unstable in 10^7 yr if $\Omega \sim 30 \text{ km s}^{-1} \text{ pc}^{-1}$. This is still a high rate of rotation for a molecular cloud, but is an order of magnitude below the initial estimate. In order for the theory to be viable, this would have to be indicative of the rotation rate achieved by a cloud after contraction. Spectroscopic observations of the Uchida et al. (1996) complex would therefore be extremely interesting. As we mentioned above, one cloud in the Galactic centre does seem to be rotating at a rate approaching this value.

6 Discussion

We have summarised the observational situation and a number of theories for the curious filaments in the Galactic centre, and have discussed at some length our own theory for the Snake. In the process of this brief review and summary of one theory, has anything been learned? The answer to this question is necessarily subjective and other workers in this field would answer this in entirely different ways. From a purely subjective viewpoint therefore, it seems to us that reconnection driven by some dynamical process together with electron diffusion and synchrotron cooling are the essential ingredients for a comprehensive theory of these filaments. There is good (circumstantial?) evidence for this: the sites of particle acceleration in the Arc are plausibly related to reconnection brought about by the interaction of molecular clouds with the magnetic field in Sagittarius A, the increase in polarised emission at the crossing of two strands in G359.54+0.18, and the coincidence of peaks in radio emission at kinks in the Snake. It also seems to us that the sometimes bifurcated, sometimes multi-stranded, sometimes braided morphology of the filaments is indicative (or at least suggestive) of the topological rearrangement of magnetic field lines resulting from reconnection. We have quoted some work on this relating to twisted magnetic flux tubes and this has motivated the model we have advanced for the Snake. Our proposal for the production of kinks and reconnection through the rotation of the anchoring clouds stands or falls by the detection or non-detection of rapid rotation in molecular cloud–HII region cores which intersect the filaments. However, there are other ways in which magnetic flux tubes may interact to provide reconnection sites. Some recent work in a solar physics context involving colliding flux tubes (albeit twisted) is that by Linton, Dahlburg, & Antiochos (2001). Whatever way reconnection is initiated, it seems that the interaction between molecular clouds and filaments is strongly related to the gas dynamics of the bar-driven accretion in the Galactic centre. Development of this theme seems to be an exciting and productive prospect and may illuminate the processes of accretion in galactic nuclei in general.

Once electrons are accelerated at a given site they diffuse and cool, the latter mainly as a result of synchrotron losses. We have summarised two models that take diffusion into account, and it is interesting to note that the diffusion parameter in each case is consistent with the

same level of turbulence and the 0.4–1 mG strength of the magnetic field. For the Snake, we have argued that radiative losses are unimportant at the observed frequencies. However, other filaments that are older in terms of their cooling timescales would be expected to exhibit cooling features in their spectra. Therefore, it is unsurprising to see a variety of spectral index characteristics in the filaments. Cooling has been successfully incorporated into the diffusive model for the southern plume (connected to the Arc) and presumably we shall soon see diffusive plus cooling models for all of the NTFs.

The issue of the particle spectrum resulting from the reconnection regions with or without associated shocks has received little attention to date. The theory of particle acceleration in shocks is well advanced, the theory of reconnection induced particle acceleration less so, although there has been some recent work in this area (e.g. Schopper, Birk, & Lesch 1999; Birk, Crusius-Waetzell, & Lesch 2001). A significant problem in the context of the filaments is what determines the parameters of the electron distribution, total energy density, minimum Lorentz factor, etc.

The strength of the magnetic field in the Galactic centre permeates all of the theoretical ideas that we have summarised. The two main contenders seem to be (1) a pervasive milligauss field, and (2) isolated instances of force-free fields. The helical field structure surrounding the Arc is good evidence for the latter and the existence of the filaments G358.85+0.47 and G359.85+0.39 parallel to the Galactic plane tend to argue against the former. However, we are sure that this will continue to be a disputed point for some time and there are counterarguments — such as the idea that the parallel filaments mark a change in direction of the Galactic centre magnetic field. Extrapolating our ideas on the Snake to other filaments, we attribute the predominance of filaments perpendicular to the plane to the lack of shear induced disruption for filaments in this direction. (This point arose in discussion with Professor Ron Ekers following the presentation at the Festschrift.)

Acknowledgements

We are grateful to an anonymous referee for constructive comments, and to Professors Ken Freeman and James Binney for useful discussions.

References

- Alfvén, H. 1950, *Cosmic Electrodynamics* Princeton Series in Astrophysics (Oxford: Clarendon Press)
- Amo, H., et al. 1995, *Phys. Rev. E*, 51, 3838
- Anantharamaiah, K. R., Lang, C. C., Kassim, N. E., Lazio, T. J. W., & Goss, W. M. 1999, in *The Central Parsecs of the Galaxy*, ASP Conf. Ser. 186 (San Francisco: Astronomical Society of the Pacific), 507
- Anantharamaiah, K. R., Pedlar, A., Ekers, R. D., & Goss, W. M. 1991, *MNRAS*, 249, 262
- Ballesteros-Paredes, J., Vázquez-Semadeni, E., & Scalo, J. 1999, *ApJ*, 515, 286
- Basu, S., & Mouschovias, T. Ch. 1995a, *ApJ*, 453, 271

- Basu, S., & Mouschovias, T. Ch. 1995b, *ApJ*, 452, 386
- Bazdenkov, S., & Sato, T. 1998, *ApJ*, 500, 966
- Benford, G. 1988, *ApJ*, 333, 735
- Benford, G. 1997, *ApJ*, 333, 735
- Bicknell, G. V., & Li, J. 2001, *ApJ*, 548, L69
- Bicknell, G. V., & Melrose, D. B. 1982, *ApJ*, 262, 511
- Binney, J. 1974, *MNRAS*, 168, 73
- Birk, G. T., Crusius-Waetzel, A. R., & Lesch, H. 2001, *astro-ph/106565*
- Blandford, R. D., & Ostriker, J. P. 1978, *ApJ*, 221, L29
- Brown, R. L., & Liszt, H. S. 1984, *ARAA*, 22, 223
- Chandran, B. D. G., Cowley, S. C., & Morris, M. 2000, *ApJ*, 528, 723
- Gray, A. D., Cram, L. E., Ekers, R. D., & Goss, W. M. 1991, *Nature*, 353, 237
- Gray, A. D., Nicholls, J., Ekers, R. D., & Cram, L. E. 1995, *ApJ*, 448, 164
- Heitsch, F., Mac Low, M., & Klessen, R. S. 2001, *ApJ*, 547, 280
- Heyvaerts, J., Norman, C., & Pudritz, R. E. 1988, *ApJ*, 330, 718
- Killeen, N. E. B., Lo, K. Y., & Crutcher, R. 1992, *ApJ*, 385, 585
- Kraichnan, R. H. 1965, *Phys. Fluids*, 8, 1385
- Lang, C. C., Anantharamaiah, K. R., Kassim, N. E., & Lazio, T. J. W. 1999, *ApJ*, 521, L41
- Lang, C. C., Morris, M., & Echevarria, L. 1999, *ApJ*, 526, 727
- LaRosa, T. N., Kassim, N. E., Lazio, T. J. W., & Hyman, S. D. 2000, *AJ*, 119, 207
- LaRosa, T. N., Lazio, T. J. W., & Kassim, N. 2001, *astro-ph/0108360*
- Lesch, H., Crusius, A., Schlickeiser, R., & Wielebinski, R. 1989, *A&A*, 217, 99
- Li, J., & Melrose, D. B. 1994, *MNRAS*, 270, 687
- Linton, M. G., Dahlburg, R. B., & Antiochos, S. K. 2001, *ApJ*, 553, 905
- Liszt, H. S., & Spiker, R. W. 1995, *ApJS*, 98, 259
- Melrose, D. B. 1982, *Plasma Astrophysics* (London: Gordon & Breach)
- Mestel, L. 1999, *Stellar Magnetism: The International Series of Monographs on Physics* (Oxford: Clarendon Press)
- Mestel, L., & Paris, R. B. 1984, *A&A*, 136, 98
- Molvig, K. 1975, *Phys. Rev. Lett.*, 35, 22
- Morris, M. 1998, in *The Central Regions of the Galaxy and Galaxies*, IAU Symposium (Dordrecht: Kluwer) 184, 331
- Morris, M., & Serabyn, E. 1996, *ARAA*, 34, 645
- Morris, M., & Yusef-Zadeh, F. 1985, *AJ*, 90, 2511
- Morris, M., & Yusef-Zadeh, F. 1989, *ApJ*, 343, 703
- Nicholls, J., & Le Strange, E. T. 1995, *ApJ*, 443, 638
- Ormes, J. F., & Protheroe, R. J. 1983, *ApJ*, 272, 756
- Padoan, P., & Nordlund, A. 1999, *ApJ*, 526, 279
- Plante, R. L., & Crutcher, R. M. and K. Y. Lo 1999, in *The Central Parsecs of the Galaxy*, ASP Conference Series 186, eds H. Falcke, A. Cotera, W. J. Duschl, F. Melia, & M. J. Rieke (San Francisco: Astronomical Society of the Pacific), 483
- Pohl, M., Reich, W., & Schlickeiser, R. 1992, *A&A*, 262, 441
- Ptuskin, V. S., Lukasiak, A., Jones, F. C., & Webber, W. R. 1999, in *26th International Cosmic Ray Conference*, eds D. Kieda, M. Salamon, & B. Dingus (New York: AIP) 4, 291
- Reich, W. 1990, in *Galactic and Intergalactic Magnetic Fields*, IAU Symposium 140, eds R. Beck, P. Kronberg, & R. Wielebinski (Dordrecht: Kluwer), 369
- Roberts, D. A. 1999, in *The Central Parsecs of the Galaxy*, ASP Conference Series (San Francisco: ASP) 186, 483
- Rosner, R., & Bodo, G. 1996, *ApJ*, 470, L49
- Ruzmaikin, A. A., Shukurov, A. M., & Sokoloff, D. D. 1987, *Magnetic Fields of Galaxies* (Dordrecht: Kluwer)
- Saha, P., Bicknell, G. V., & McGregor, P. J. 1996, *ApJ*, 467, 636
- Schopper, R., Birk, G. T., & Lesch, H. 1999, *Physics of Plasmas*, 6, 4318
- Serabyn, E., & Morris, M. 1994, *ApJ*, 424, L91
- Shore, S. N., & LaRosa, T. N. 1999, *ApJ*, 521, 587
- Sofue, Y., & Fujimoto, M. 1987, *PASJ*, 39, 843
- Uchida, K. I., Morris, M., Serabyn, E., & Güsten, R. 1996, *ApJ*, 462, 768
- Webber, W. R., Lee, M. A., & Gupta, M. 1992, *ApJ*, 390, 96
- Yusef-Zadeh, F., & Morris, M. 1987, *ApJ*, 322, 721
- Yusef-Zadeh, F., Morris, M., & Chance, S. 1984, *Nature*, 310, 557
- Yusef-Zadeh, F., Wardle, M., & Parastaran, P. 1997, *ApJ*, 475, L119