in particular show the two new arched filaments to the south-east and the two parallel layers on the Sgr B2 side of the Arc. The extension of the Arc to the north-west visible in Fig. 3 can also be seen in 10.5-GHz Nobeyama data filtered to remove large-scale background structure (Fig. 8 of ref. 9), and appears to indicate a smooth continuation to the large-scale ($\sim 1° \times 1°$) 'Sofue lobe'[9,10] which extends to northern galactic latitude $b \sim 0.5°$ before reconnecting to the plane at Sgr C. The apparent absence of a comparable lobe at negative galactic latitudes, however, and the nevertheless remarkably symmetrical structure of the polarization components A, B and C and of the Arc and its extensions as observed here, suggest that caution is required in identifying the Sofue lobe directly as a continuation of the Arc. There exists also a problem with reconciling the apparent one-dimensional geometry of the filaments[1] with the implied two-dimensional geometry of the Sofue lobe, if interpreted as a limb-brightened cylinder[9,10]. It is more probable that the Arc and the polarization structure are phenomena causally related to the lobe, but with different emission and supporting mechanisms. What is suggested, however, is the strong possibility that similar phenomena will be seen at the point where the lobe (or western spur as seen in the Altenhoff *et al.*[5] map at $l \sim -0.6°$) reconnects with the galactic plane. A $\lambda = 20$ cm VLA map of this region[11] already indicates the existence of a bar-like feature at this point, perpendicular to the plane, and similar in appearance to the Arc.

The core/lobe polarization structure seen in Fig. 2 is reminiscent of the total intensity picture of a classical double radio source, and seems to argue compellingly for the core position as being a centre of activity, perhaps associated with some ejection phenomenon. Recent 160-MHz observations[12] show that the only low-frequency emission visible from the Arc is also from this position, again arguing for its special status. Early 10.7-GHz observations[2] mention the existence of a nonthermal source in a position very close to the core (GO.16–0.15) where recombination lines were absent. However, recent total intensity pictures of this region at high frequencies (our Fig. 1 or Fig. 1 of ref. 1), do not distinguish the region at all—it appears to be a smoothly connected part of the filamentary structure. This is a major obstacle to any interpretation involving ejection from this position as the explanation of the Arc or the polarization lobes.

To get around this, we may extend the suggestion put forward in ref. 12. The structure seen in polarization and low-frequency emission may be the result of obscuration by a non-uniform screen of thermal material, threaded by the ambient magnetic field, which attenuates at low frequencies and depolarizes the underlying assumed synchrotron radiation. (That the underlying radiation is synchrotron seems certain from the high percentage polarizations, 30% in the outer lobes and on smaller scales in component A[12], and from the extreme linear geometry of the filaments, suggesting a magnetic field as the underlying organizing agent.) Some support for this suggestion comes from the observation that component A lies in a large gap symmetrically placed with respect to the arched filaments (Fig. 1). Thus if material were being fed along the arched filaments from the vicinity of the galactic nucleus as part of a supply of matter to the envelope surrounding the vertical filaments, it might be the case that only close to the termination point of the filaments on the Arc would sufficient material accumulate to flatten the spectral index and depolarize the underlying synchrotron radiation. The amount of material required for this purpose is estimated in ref. 12 at a few tens to a few hundreds of solar masses, although the suggestion is made that the material originates from the ambient gas surrounding the vertical filaments[13], rather than from Sgr A itself. Against this explanation, however, is the circular appearence of the central component A and the two small blobs of polarized emission either side of it pointing to the lobes (Fig. 2). This would seem difficult to generate via non-uniformities in an intervening screen without artificial assumptions as to the screen's geometry. Higher resolution polarization observations[12] show that component A is rather less ordered than suggested by its appearance in our observations, so this objection may be irrelevant. Also, the symmetry of B and C extends only to general appearance and percentage polarization and not to their detailed morphology so that again an explanation in terms of the effects of screening material is not ruled out. The general symmetry evident might in any case be expected on the basis of an approximate symmetry in distribution of screening material with respect to the galactic plane.

The nature of the polarization structure and its central component is so far unclear, as is its stability and lifetime. (It does not, unlike the Arc itself, lie along a surface of constant angular velocity in the Oort mass distribution[14].) However, it is clear that it must be reconciled with any general picture of activity at the galactic centre. Such a picture would seem now to have to include a 'chimney' of buoyant outflowing material (the Sofue lobe) similar to that seen in optical emission as a spur in the Crab nebula[15] and in radio emission as one-sided lobes in other spiral galaxies[16]. The appearance of the Arc feature and the polarization structure at the point where the chimney crosses the galactic plane, will certainly prove to be important in understanding the complexities of the galactic centre.

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Origin of the galactic centre lobes

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Recent observations of the 10-GHz continuum[1] have indicated that there is a pair of lobes having ridges of intensity extending from the galactic centre region in a direction perpendicular to the galactic plane. This observation has attracted considerable attention as it is clearly an indication of dynamic processes occurring at the centre of our Galaxy that are similar to those occurring in the nuclei of radio galaxies, though different in scale and in strength[2]. Here we interpret these lobes as being due to a magnetodynamic acceleration mechanism in which the production and relaxation of the magnetic twist induced by the rotation of the contracting gas disk play a part. The plasma is accelerated in a conical cylinder with a helical velocity field, reproducing the observed feature of radio lobes.

The structure (referred to as GCL, for galactic centre lobes) that is located on both sides of Sgr A with some asymmetry, has proved to have further interesting features. Yusef-Zadeh *et al.*[3] showed by means of high-resolution Very Large Array (VLA) observations that a source related to the galactic centre has a very peculiar structure. The structure, called the galactic centre radio arc (GCRA), is embedded in the galactic dust and has a

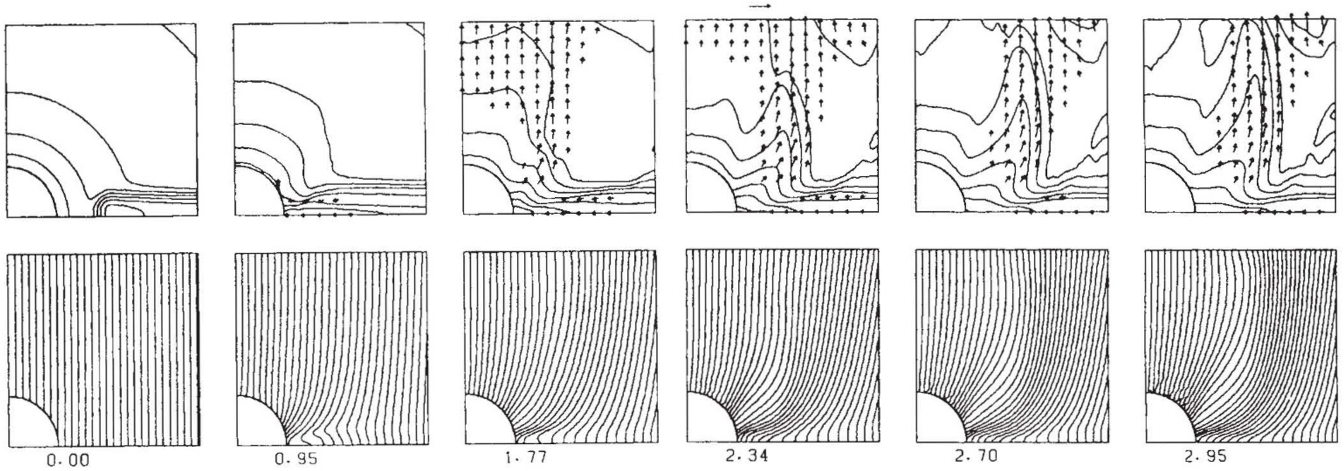

Fig. 1 Evolution with time of: upper sequence, the poloidal velocity vector, $v_{\parallel}$ $(= v_r,\ v_z)$, overlain on the density contour; lower sequence, the poloidal magnetic field lines, $B_{\parallel}$ $(= B_r,\ B_z)$. The numbers below each figure represent units of τ. It can be seen that a hollow cylindrical flow of denser material just like GCL is formed as the magnetic twist accumulated by the rotation of the disk starts relaxing toward the z-direction. The circle at the centre indicates the inner free boundary for the calculation.

thread-like appearance, strongly suggestive of magnetic fields, with one part lying vertically just at the foot, and in the extension, of the eastern ridge of GCL. The other part connects the north end of this vertical thread-like structure to Sgr A. Recent VLA observations[4] show that a similar structure is found at the foot of the western ridge of GCL. By measuring the multi-band polarization of the eastern ridge at 10 GHz, Inoue *et al.*[5] found that the polarization has peaks at both ends of the vertical part of the GCRA, and the sense of Faraday rotation is opposite at the north and south ends. A further measurement of Faraday rotation-corrected polarization (M. Tsuboi and M. Inoue, personal communication) reveals that the line-of-sight magnetic field component along the eastern ridge of GCL is directed towards us on its northern arm and away from us on its southern arm. The direction of the projected component of the magnetic field is parallel to the ridge of GCL, and the degree of linear polarization is as high as several tens of per cent. These observations suggest strongly that the entire process which led to the ejection of GCL is related to the magnetic field.

As for the formation of double radio lobes associated with radio galaxies and quasistellar objects, it has been suggested that the magnetic field and rotation might have important roles[6,7]. More recent theoretical studies have attributed the formation of these lobes to the guiding of the strong wind from their source by the funnel structure in the thick disk surrounding the source of these objects[8-11], with a few noting the importance of the magnetic field in the formation of jets[12-15]. For our Galaxy, however, before the discovery of the GCL it was believed that the activity, if it existed, was too weak to produce such phenomena.

Here we propose a magnetodynamic mechanism which explains the production of GCL by the combined effect of the rotating disk and of the magnetic field near the galactic centre. The mechanism relies on the continual production of a magnetic twist by the rotation of the disk around the galactic centre; the unequilibrated magnetic pressure gradient built up near the surface of the disk in this process causes the relaxation of the magnetic twist to the $\pm z$ directions, pushing out the plasma with helical velocity. We describe in the following the method used and the results obtained.

Consider a rotating accretion disk which entwines a part of the large-scale magnetic field. A system of ideal magnetohydrodynamic equations, in a pseudo-three-dimensional formulation, for a cylindrical symmetry ($\partial/\partial\varphi = 0$, but allowing φ-components of vector quantities) is solved numerically using a modified Lax-Wendroff scheme. A set of non-dimensional parameters (R_1, R_2 and R_3) specifies the physical situation of the problem under consideration, where $R_1 \equiv v_s^2/v_K^2$, $R_2 \equiv V_A^2/v_K^2$ and $R_3 \equiv v_{rot}^2/v_K^2$, and $v_s \equiv (\gamma RT)^{1/2}$, $V_A \equiv B/(4\pi\rho)^{1/2}$, $v_K \equiv (GM/r)^{1/2}$, the R_is representing the relative importance of the pressure gradient force, the Lorentz force, and the centrifugal force with respect to the gravity force, respectively. (v_{rot}, rotation velocity; v_K, keplerian velocity). A similar solution may hold if the set $(R_1, R_2, R_3)_0$ at a point near the inner edge of the disk, as well as the initial distributions of quantities in the relative coordinate, r/L, (where r is the radius and L is the typical scale of the problem) are the same. The timescale differs from case to case as $\tau = L/v_K$.

Values of R_i are determined for the galactic centre region as follows: Mezger and Pauls[16] have demonstrated the existence of an extended cloud of H II with a thickness and diameter of $\sim$100 pc and 300 pc, respectively, a mean ionized gas density $\rho \sim 10\ m_H\ cm^{-3}$ (m_H is hydrogen mass), and an electron temperature of 5,000 K. The total mass involved in the part of the disk with $r \leq 60$ pc (mean distance of the east and west ridges of the lobes) from the galactic centre (Sgr A) is $\sim 3\times10^8\ M_{\odot}$, and the rotation velocity at $r = 60$ pc is $\sim$180 km s^{-1}, as derived from the H I and CO line observations of the galactic centre region[17]. The magnetic field strength may be roughly evaluated by applying the equipartition law for energy densities of high-energy electrons and the magnetic field; using our 10-GHz radio continuum data for the galactic centre region[2], we obtain $B \sim 2\times10^{-5}$ G at the location of the GCRA. From these quantities we obtain $v_s = 8$ km s^{-1}, $V_A = 14$ km s^{-1}, in the disk near the GCRA. These quantities yield the set of parameters $(R_1, R_2, R_3)_0 \sim (1.8\times10^{-3}, 6.1\times10^{-3}, 1-\delta)$ where δ is a small fraction of unity, assuming that the part of the disk under consideration is rotating at a sub-keplerian velocity and is still in the contracting stage. It is interesting that the set of non-dimensional parameters thus derived is not very different from that for a corresponding point $(3.0\times10^{-3}, 7.2\times10^{-3}, 1-\delta)$ in the protostellar case examined previously[15]. Thus, we may expect that the outflows from the galactic centre region will be similar (though very different in scale) to those in the star-forming regions, which, in our view, also result from the magnetic field becoming twisted up in the rotational motion of the contracting accretion disk towards the end of the star-formation process.

Figures 1 and 2 show the result of numerical simulations for the present situation. The calculation is preliminary because we assumed that the effective gravity source is a point mass at the centre. Cases corresponding to a more realistic situation in the galactic centre region are now being dealt with, and a fuller discussion of such cases, which confirm the basic validity of the present result, will be published elsewhere[18].

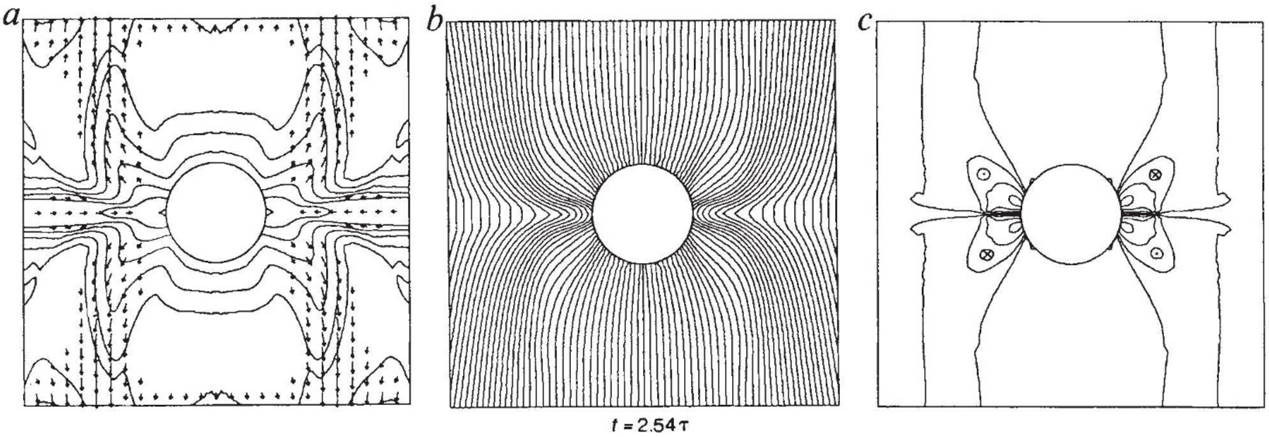

Fig. 2 *a*, The poloidal velocity vector overlain on the density contour. *b*, The poloidal magnetic field lines. *c*, The contour of the toroidal magnetic field strength, B_φ. (All parameters at $t=2.54\tau$.) It can be seen in *b* that the poloidal magnetic field has a vertical component in the disk, together with some other field lines obliquely connected to the inner part, corresponding to the vertical and oblique structures of the GCRA. From *c*, it can be seen that the toroidal component has opposite polarities on both sides of the equatorial plane, as Inoue *et al.*'s observation indicates[5].

Figure 1 shows the time development after a disk is formed in a plane perpendicular to the large-scale magnetic field, and is still contracting ($R_3<0$). The circle at the centre is the inner free boundary for the calculation. The upper sequence (overlay of the velocity field projected on the density contour in the r-z plane) shows that, following the preceding fast-mode front due to the squeezing around the axis of rotation, there appears a denser flow rising with a horn-shaped profile, corresponding to a hollow conical cylinder in three dimensions. Figure 2 shows the situation at $t=2.54\tau$ ($\tau\equiv L/v_K$ at $r=L$) in full, as an example. The poloidal magnetic field $B_\parallel$ ($=B_r, B_z$) is pulled both inwards and into the φ-direction by the contracting rotation of the disk, and the toroidal field B_φ is produced continually. The accumulated B_φ relaxes along $B_\parallel$ as a magnetic-twist front. The signs of B_φ above and below the plane of the disk are opposite because it is produced by the rotating disk winding up the poloidal field. Clearly, the energy of the cylindrical flow derives from the rotational energy of the dense part of the disk, mediated by the action of the magnetic field. The unequilibrated gradient in B_φ, which is continually produced by the effect of rotation, pushes up the mass of the less dense (but dense enough to make high contrast in the halo) surficial region of the disk into a conical jet.

It is readily noted from Figs 1 and 2 that the density contour has a similarity to GCL observed by Sofue and Handa[1], and that the near-disk configuration of $B_\parallel$ and the distribution of B_φ may explain the shape of the GCRA and the reversal of the line-of-sight component of the magnetic field[5,6]. It is characteristic of our mechanism that the velocity field has v_φ (though not shown here) which, together with $v_\parallel$, yields a helical velocity field. The velocity of the outflow is of the order of 150-200 km s^{-1}, and the rotational velocity near the disk and near the front is of the same order as this, but is considerably less in between. Preliminary results from the observation of GCL in CO lines, now being done using the Nagoya University 4m mm-wave telescope (I. Suwa, Y. Fukui, Y. S. and T. Handa, personal communication) suggest that the observed velocity field is not inconsistent with our model.

We require some support for our assumptions, for example, the assumption that the initial magnetic field is perpendicular to the plane of the disk, and $R_3\equiv v_{\rm rot}^2(r)/v_K^2<1$. The former assumption, which seems to be observationally actually the case with the star-forming regions[19], is likely to be relevant in a wide variety of condensations of the magnetized mass. This is because it is easier for the initial condensation to occur along B_0 than perpendicular to it[20], and also because the angular momentum component perpendicular to the magnetic field in the initial cloud tends to be damped in the earlier phase of contraction, and the component parallel to B_0 remains[21,22]. Although the magnetic field in the galactic arms is largely aligned with the arm structure, it is possible that the magnetic field in the galactic centre part has poloidal components. The observations in refs 3, 5 and by Tsuboi *et al.* (personal communication) strongly support this notion.

The second assumption—that $R_3<1$—is obviously the case if the accreted gas is still outside its Kepler radius. Even after it reaches the Kepler radius, however, the condition $R_3<1$ may be brought about in the final phase of accretion due to the loss of angular momentum by the production of the magnetic twist and the mass ejection by the present mechanism. The rotation is thus braked ($R_3<1$), and the disk mass can continue to fall spirally toward the centre of gravity[18]. A larger amount of energy is released and can be converted to that of the bipolar jet as the centre is approached, since the mediator, the magnetic field, gains strength in the compression and winding up operates more effectively.

Finally, note that the process discussed here may be either a continuous process or a train of discrete events, depending on the supply of magnetized material. Similarly, the process can be asymmetric with respect to the axis or the equatorial plane, if there is such an asymmetry in the distribution of the density or magnetic field in the accreted cloud, although the calculation was performed by assuming axisymmetry as an idealization.

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