The kinematic centre of the Galaxy

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Summary. The discovery of a hot optically thin molecular hydrogen ring around the Galactic nucleus provides the first good opportunity of ascertaining whether the velocity field in the central region of the Galaxy is approximately axially symmetric. In addition, it is possible to deduce the absolute value of the non-circular component of the LSR motion from the systemic velocity of the ring.

1 The 40 km s⁻¹ cloud

Surrounding the extremely compact non-thermal radio source Sgr A* at the centre of our Galaxy is a complex of high-velocity ionized gas at R≤1 pc (Lacy et al. 1980), indicating that a massive collapsed object may be present (Rees 1982). Also observed are the time variable e⁺e⁻ annihilation γ-ray line at 511 keV (Lingenfelter & Ramaty 1982) and the very broad (~1500 km s⁻¹) He I emission line at 2.06 μm (Hall, Kleinmann & Scoville 1982). The central source may therefore be intermittently active and associated with mass outflow. Such findings may not be inconsistent (e.g. Lo 1984) with an exceptional past explosion at the centre of the Galaxy (Oort 1977) having given rise to the large-scale motions in H I and molecular gas within R≤3 kpc. The evidence is of course circumstantial and does not immediately enlighten us as to the physical nature of any such explosion, should it have happened, nor of the Galactic circumstances giving rise to it. But if the picture is broadly correct and such explosions and outwardly moving streams of material are of the same general character as those observed in the nuclei of other active galaxies, an understanding of the nature of recurrent nuclear activity may be arrived at through an analysis of the Galactic velocity field within 1≤R≤3000 pc. It is conceivable also, of course, that the observed velocity field does not reflect a short-lived explosive phenomenon but a rather random distribution of gas clouds moving in a triaxial potential field due to a bar-like mass at the centre (Cohen & Davies 1979; Liszt & Burton 1980); other possibilities include precessing jets (Brown 1982), density waves (but see Ekers et al. 1983) and the tidal disruption of infalling clouds (Güsten & Downes 1980). The ambiguity concerning the physical nature of the large-scale motions is clearly fundamental and may be partly attributed to uncertainty regarding the precise
standard of rest in the centre of the Galaxy. One notes for example in the conclusion of a recent review (Brown & Liszt 1984, hereafter BL) the particular emphasis placed on ‘the kinematical centre of the galaxy, as measured by stellar kinematics, [having] not been established’.

The self-evident nature of BL’s conclusion may cause us to overlook its full significance. It is worth emphasizing the implications of what is being said therefore. The essential points are: (i) it is necessary to know the Galaxy’s dynamical centre if we are to progress; (ii) the dynamical centre is in principle detectable if it lies at the (kinematical) centre of a demonstrably symmetric velocity field; and (iii) stars are well-mixed tracers of the Galactic mass distribution and are expected to display a kinematic symmetry that gaseous tracers are currently believed not to reveal. Since adequate stellar velocities in the Galactic bulge have not yet been measured, the fundamental difficulty at present is the failure to detect symmetry in the velocity field associated with gaseous tracers. Pattern recognition is not a straightforward business however and one can never be certain in practice that all possibilities in a search for symmetry have been exhausted. The problem is that underlying symmetric patterns can often assume asymmetric forms. An upright cube for example with alternate sides painted black and white and viewed from the side at random azimuth, will appear disproportionately black or white as the case may be. An inferred pattern may therefore exist in the eye of the beholder as much as in Nature and cannot be accepted without a post hoc justification of its physical basis. This may be simple enough if the appropriate physical theory is at hand, but when the character of the underlying process is itself unresolved, as in galactic nuclei, the whole procedure becomes somewhat more open-ended and it is necessary to advance with considerably greater caution. Possibly the only way forward in these circumstances is to take advantage of an underlying symmetry inferred from apparently asymmetric forms to predict symmetric patterns that are capable of later experimental verification. Subsequent verification might then admit of only one kind of physical solution which may or may not place an important constraint on physical theory.

By way of illustrating how these considerations might affect our understanding of the Galactic centre, we could for example assume that there has been a symmetrical central explosion and that the subsequent condensations (e.g. clouds) reflect the resultant state of either the surrounding medium or the ejected material. Observed streams of ejected material would then be shock-heated on their leading or trailing edges depending whether they are slowed or accelerated by the ambient medium. Thus, although the relative luminosity $r = L_c/L_0$ of gaseous tracers for exterior (e) and interior (i) aspects of symmetrically distributed material will have ~unit value for small optical depths $0 \leq \tau < 1$, values differing considerably from unity can in principle arise when $\tau > 1$. In our Galaxy for example, the most conspicuous arms within $R \sim 3$ kpc are the so-called ‘3 kpc’ and ‘+135°’ arms possessing approximate geometric symmetry, $r \sim 3$ and observed radial components of motion relative to the local standard of rest of $-55$ and $+135$ km s$^{-1}$ respectively (Rougoor 1964). Their supposed explosive formation might therefore be asymmetric (i.e. $\Pi_{LSR} \approx 0$ km s$^{-1}$, $0 \leq \tau < 1$; Rougoor 1964) or symmetric (i.e. $\Pi_{LSR} \approx 40$ km s$^{-1}$, $\tau > 1$; Clube 1978). In fact, large $r$s are not uncommon in galactic H i clouds (Radhakrishnan et al. 1971), particularly in the 3-kpc arm (Rougoor 1964), and spirals often exhibit ‘grand design’ in their central regions. The second alternative cannot therefore be excluded a priori even though the introduction of a non-zero motion for the LSR would appear to give rise to more problems than it solves. Indeed, a non-zero value of $\Pi_{LSR}$ approximating to the symmetrical ejection value may already be implicit in the as yet unexplained $\Pi$-distribution of Galactic globular clusters and halo RR Lyrae stars near the centre (Clube & Watson 1979; cf. Frenk & White 1980) and in the as yet unconfirmed proposal that Kapteyn’s stream II best defines the Galactic standard of rest in the solar neighbourhood (Clube 1983a). The implication in this latter case is that the Sun is surrounded by the relatively old stellar disc but also immersed in a locally more dominant star-forming complex of linear dimensions $\sim 10^2$ pc, mass a few $10^6 M_\odot$ and age $\sim 3 \times 10^7$ yr.
(Olano 1982; Lindblad et al. 1984; Stothers & Frogel 1974). On this picture, the 'stationary' disc corresponds to Kapteyn's stream II and the local complex to stream I, the mean motion of the latter having an outward component relative to the spiral arm system in the wider solar neighbourhood of $\sim 10 \, \text{km} \, \text{s}^{-1}$. Since stream I is observed to have an outward component in the Galaxy relative to stream II of $\sim 40 \, \text{km} \, \text{s}^{-1}$, a motion of the nuclear region of this magnitude relative to the LSR is a distinct possibility. It is clear therefore that the location of the so-called 40 km s$^{-1}$ molecular cloud in the general direction of Sgr A (now often called the 50 km s$^{-1}$ cloud) may be an issue of fundamental importance (cf. Balick & Heckman 1982). Several authors (e.g. Schwarz, Shaver & Ekers 1977; Ekers et al. 1983; BL) have emphasized that it is already difficult to avoid a very close association between Sgr A and the 40 km s$^{-1}$ cloud, so the question naturally arises whether it is merely a physically unimportant (i.e. random) feature near the nucleus or whether it reflects the organized velocity field in the central region.

2 A possible structure for the central region

The Galactic centre is currently assumed to be at the core of the stellar distribution IRS 16, which is here taken for convenience to be at the origin of a self-explanatory coordinate system ($\Delta l$, $\Delta b$). It is possible that Sgr A$^*$, though very close to the centre, is slightly displaced from it (Storey & Allen 1983) and endowed with proper motion (Backer & Sramek 1982). The region within ~50 pc of the centre, as projected on the sky, is however dominated by three fairly distinct continuum sources of ionized gas, namely (i) the central source Sgr A comprising Sgr A$^*$ at ~$(0, 0)$, its surrounding halo Sgr A west and a possible supernova remnant Sgr A east; (ii) a non-thermal spur at $\Delta l=0^\circ.20$; and (iii) a bridge of predominantly thermal emission from diffuse gas mostly somewhat above ($\Delta b \sim +0^\circ.05$) and slightly inclined ($\sim 5^\circ$) to the plane, linking Sgr A to the spur (see Fig. 1). Below Sgr A, similarly inclined and similarly displaced ($\Delta b \sim -0^\circ.05$), there is a ridge of molecular gas extending to $|\Delta l| \sim 0^\circ.15$ though with somewhat greater intensity

![Figure 1. The 2.8-cm radio continuum and ammonia emission in the (1, 1) transition from the Galactic centre region (derived from BL fig. 5), the position of the centre being indicated by a cross.](https://academic.oup.com/mnras/article-abstract/216/3/511/1005971/1005971)
Figure 2. Mean velocity for three H$_2$CO features as a function of distance parallel to the plane from Sgr A west (the Galactic centre). The outer measurements producing a shallow gradient ($\sim$3 km s$^{-1}$ arcmin$^{-1}$) are taken from Güsten & Downes (1980) whilst the steeper gradient ($\sim$6 km s$^{-1}$ arcmin$^{-1}$) is derived from observations by Sandqvist (1982). These patterns, taken in conjunction with the even steeper H i gradient ($\sim$100 km s$^{-1}$ arcmin$^{-1}$) centred on the large filled circle and within 0.5 arcmin of Sgr A west (BL), are consistent with a trend of radially diminishing differential rotation and a systemic motion of $\sim$40 km s$^{-1}$.

towards negative longitudes. The so-called 40 km s$^{-1}$ cloud extending to $|\Delta l| \sim 0^\circ.05$ is more or less centrally placed in the molecular ridge though its peak emission occurs at $(\Delta l, V) \sim (0^\circ.03, 50 \text{ km s}^{-1})$. The velocity gradient along the ridge is self-evidently consistent with an organized pattern of differential galactic rotation having a systemic velocity very close to 40 km s$^{-1}$ (see Fig. 2). A diffuse X-ray emission of unknown origin, possibly from large numbers of T Tauri stars (BL), comes in order of increasing intensity from the general area of the molecular ridge, the ionized bridge and Sgr A. Details apart then, the general impression is of a somewhat structured, thick central disc ($\delta \Delta l \times \delta \Delta b \sim 50 \times 20 \text{ pc}^2$) with several of the characteristics of star-forming regions, bounded at the positive longitude end by a non-thermal spur.

No clear picture exists as yet regarding the physical location of the above features but some authors have ventured to attach significance to the juxtaposition of the relatively sharp positive longitude boundary of the molecular ridge and the ionized spur (BL), star formation in a region of sharp compression perhaps being implied. But since the spur (i) appears to be continuous with a huge coherent shell extending far beyond the molecular cloud $\sim$200 pc off-centre from the nucleus (Altenhoff et al. 1978; Sofue & Handa 1984) and (ii) comprises several narrow strands in the zone of apparent contact rather than a series of H ii regions (Yusef-Zadeh, Morris & Chance 1984), the grounds for suggesting the above kind of physical association are not particularly secure. Admittedly the spur remains a comparatively unique phenomenon and the circumstantial evidence does not exclude some new type of association with the nucleus (e.g. magnetic: Yusef-Zadeh et al. 1984), but the possibility also exists that it is not interacting with the nuclear region at all and that it is not fundamental to any understanding of the Galactic centre. The spur then may or may not be associated with the central disc.

The assumption of an association has not to date led to any far-reaching clarification of the central structure, but if one adopts the alternative view that there is no association, the strongest parts respectively of the ionized bridge and the molecular ridge become the most prominent features. These appear to be more or less symmetrically disposed about Sgr A, thus raising the
possibility that they respectively correspond to exterior and interior aspects of symmetrical arms in front of and beyond the centre which are located in a differentially rotating central disc inclined to the Galactic plane. This hypothesis is not inconsistent with the appearance of small and large emission peaks in the 40 km s\(^{-1}\) cloud respectively above and below Sgr A (see Fig. 3) and the greatly reduced molecular absorption at this velocity in the direction of Sgr A\(^*\) (Whiteoak, Gardner & Pankonin 1983). Many independent arguments based mostly on H\(_i\) observations favour an inclined disc structure within \(R \leq 1.5\) kpc (Burton & Liszt 1978; Sinha 1979), whilst other possible explanations of the reduced absorption (e.g. Ekers \textit{et al.} 1983) are not very likely because they either place Sgr A\(^*\) in front of Sgr A west or require an \textit{accidental} hole exactly in the direction of the centre. The assumption that we are dealing with a distribution at \(R \sim 10\)–50 pc approximating to an inclined ring of material around the centre evidently allows of the possibility of a comparatively unimpeded view of the nuclear region. It follows that inclined neutral and ionized tracers (of spiral arms?) might, if a symmetric velocity field is involved, be expected to reveal an even higher gradient of differential galactic rotation close to the centre at the systemic velocity of 40 km s\(^{-1}\). Such a velocity field is apparently observed in the most recent VLA observations at H\(_i\) (Liszt & Burton 1984) and also to some extent in the spatially less well resolved O\(_i\) observations at 63 \(\mu\)m (Genzel \textit{et al.} 1982; but note also Genzel \textit{et al.} 1984). It may be noted also that the \(e^+e^-\) annihilation line formed \(\leq 1\) pc from the central engine is \(\approx \pm 145\) km s\(^{-1}\) broad and redshifted by \(\sim 55\) km s\(^{-1}\) (Lingenfelter & Ramaty 1982). The standard error of this redshift is rather high however, so this particular observation, whilst indicating a motion in provisional accord with the systemic velocity of 40 km s\(^{-1}\), is not well enough established to confirm the prediction.

However, by positively rejecting any association between the ionized spur and the molecular ridge, one arrives at a picture of inclined symmetric ejection which is broadly consistent with

![Figure 3](https://academic.oup.com/mnras/article-abstract/216/3/511/1005971/fig3)

\textbf{Figure 3.} Contours of \(^{12}\)CO intensity integrated over the range 40\(\leq V\leq 60\) km s\(^{-1}\) showing the extent of the 50 km s\(^{-1}\) molecular cloud (as derived by BL). These are superposed on an outline of the radio continuum distribution, thus indicating the position of the so-called spur relative to a proposed compression zone (BL) at the molecular cloud's positive longitude boundary (see text). Note in particular the intensity minimum in \(^{12}\)CO just above the Galactic centre (cross), indicating the presence of a window at or just above centre.
much of the data as it currently stands. The 40 km s\(^{-1}\) cloud does certainly appear to be part of the organized velocity field at the Galactic centre, and there is a clear expectation of a symmetric velocity field centred on 40 km s\(^{-1}\) for any uniformly distributed emitter of low optical depth.

Far-infrared observations (Becklin, Gatley & Werner 1982) indicate the presence of dust in a ring-like structure \((R\approx 2 \text{ pc})\) surrounding much of the gas producing radio continuum and Ne II emission in the centre of the Galaxy. The decline in dust density interior to the ring is accompanied by an increasing concentration of luminous sources and it is possible that the ring may be centrally heated. The presence of neutral gas in the dust ring is revealed by observations of the 63\(\mu\)m \(3P_1-3P_2\) fine structure line of O I (Lester et al. 1981) and the \(V=1\rightarrow 0 S(1)\) line at 2.122\(\mu\)m from H\(_2\) (Gatley et al. 1984), the latter apparently being confined to an optically thin annulus fairly near the inner edge of the ring. However, Gatley et al. (1984) point out that the mass loss required from the central source in order to shock excite the molecular hydrogen is too large to be radiatively driven. They therefore propose a nuclear wind, but the observed molecular hydrogen could alternatively be due to hot dense material from the central source which has cooled (and implicitly recombined to form molecules) on its way to its present location. The widespread appearance of molecular hydrogen in the same general condition (e.g. Beckwith 1981, including discussion) elsewhere in the Galaxy, and in other galaxies as well, might be considered to favour this possibility but any such hypothesis that molecular hydrogen is flowing from the central object still requires detailed physical justification. Whatever the origin of the molecular hydrogen however, its existence as an apparently regular structure in the nuclear region would on the present hypothesis give rise to a symmetric velocity field at a mean velocity of 40 km s\(^{-1}\). To arrive at a model of this field, we now consider recent studies of the ionized gas in Sgr A west which have been interpreted as indicating the possible presence of a three-arm spiral close to the centre (Lo & Claussen 1983).

The strongest emission of these ‘spiral arms’ frequently correlates with the known Ne II sources (Lacy et al. 1980) and their velocity systematics thus enable some inferences about the structure to be made. Lo & Claussen for example argue that the top end of the ‘northern arm’ joined with the ‘southern arm’ clearly forms a continuous arc to the west of the centre, whilst most of the ‘eastern arm’ can be seen as comprising an incomplete but similarly displaced arc to the east. Lo & Claussen also point out that most of the remaining ionized gas constitutes a coherent bar-like feature with a north-western orientation passing just to the south of IRS 16 and Sgr A\(^*\), whose motion is discontinuous with the underlying gas. Independent observations have indicated the existence of a ‘finger of absorption’ roughly coincident with this bar (i.e. between IRS 16 and 6) which nevertheless does not obscure IRS 16 (Geballe 1984, private communication). The two arcs that have been identified seem therefore to have the appearance of an incomplete but inclined annulus whose extreme tangential lines-of-sight lie more or less within the two 100-\(\mu\)m peaks (see Fig. 4), whilst the north-western bar has the appearance of a finger or jet across the field of view that may be accidental so far as the central organization is concerned. Indeed BL in a detailed discussion of this bar, conclude that it is wholly distinct from the dust ring ‘dynamically, kinematically and thermodynamically’. If the arcs then are regarded as sections of a central ring-like structure, with the jet or bar of no fundamental importance, the Ne II velocities within the 1–2 pc annulus are then broadly consistent with a temporarily expanding field circulating at \(\Theta\sim 120\) km s\(^{-1}\) and a systemic motion fairly near to \(\Pi_{\text{LSR}}=40\) km s\(^{-1}\). Emitting species of small optical depth closely associated with a dynamically more relaxed region outside this annulus and not to any significant degree with the jet (e.g. the molecular hydrogen ring) might be expected therefore to circulate with a velocity between this extreme, \(\Theta\sim 120\) km s\(^{-1}\), on the one hand and that of the central cloud of the molecular ridge on the other, where \(\Theta\sim 20\) km s\(^{-1}\). The suggestion based on a redefinition of \(\Pi_{\text{LSR}}\) that the annulus of hot H\(_2\) may circulate at \(\sim 100\) km s\(^{-1}\) and that it is simply part of a regularly structured inclined disc whose circular velocity and temperature
merely decrease monotonically with $R$, would clearly correspond to a significant clarification of the Galaxy’s central organization.

It has to be emphasised that such inferences relate purely to possible kinematics in the central region of the Galaxy, and are independent of any presumed dynamical process that may be responsible for the observed effects. Should the LSR motion be confirmed however, it may become important to recognize the rather strong similarities that would then exist between large-scale Galactic kinematics (including spiral structure), those of the central region (including the 3-kpc and +135 arms) and those of the nuclear region ($R \leq 50$ pc). The instantaneous states of these otherwise disparate regions, each involving a relaxed disc and symmetrical expanding arms may result from rather similar prior conditions, albeit on different scales, in which the spiral arms emerge from a region at the centre of the Galaxy that has undergone a considerable degree of compression (e.g. Burbidge 1967; van der Kruit, Oort & Mathewson 1972; Clube 1978). Although analogies of this kind can be deceptive, such a finding might be important because it would be a pointer to some as yet unrecognized dynamical process drawing material together and redistributing angular momentum in the central region prior to the release of a high angular momentum component moving outwards in the Galaxy (e.g. see Clube 1983b). Indeed, if all two-arm spirals were to owe their existence to this kind of process, and the process is as ubiquitous and as common as it appears, one might also consider similarities with the variety of jet phenomena manifest on so many scales in hyperactive galaxies (e.g. Begelman, Blandford &
3 Kinematics of the molecular hydrogen ring

Recent velocity measurements of the molecular hydrogen ring have been reported (Wade 1985) and have kindly been made available to us prior to publication (Gatley, Geballe & Wade 1985, in preparation). The principal features of the velocity field are as follows:

(i) a roughly symmetrical total emission profile $I(V)dV$ over the central region $\delta \Delta l \times \delta \Delta b \sim 140 \times 80$ arcsec$^2$, containing substantial peaks at $R \sim 2$ pc on either side of the Galactic nucleus and more or less coincident with the two $100$-$\mu$m peaks.

(ii) a linear $(V, \Delta l)$ correlation parallel to the plane indicative of Galactic rotation, with the above peaks at $(140$ km s$^{-1}$, $+40$ arcsec) and $(-60$ km s$^{-1}$, $-35$ arcsec) respectively.

The distribution of emission over the region at $+40$ km s$^{-1}$ is remarkably similar to the total emission, showing that this velocity is likely to be fairly close to the systemic motion of the ring. It is particularly significant that an arc (or tail) running in a WSW direction from the $+140$ km s$^{-1}$ peak closely reflects [through $(\Delta l, \Delta b, V) = (0, 0, +40)$] the geometry and velocity of an arc (or tail) running in an ENE direction from the $-60$ km s$^{-1}$ peak. Although the exterior–interior aspect apparently inverts along each arc (as might be expected for near tangential lines-of-sight), the value of $r$ remains at $\sim 1.3$ implying a maximum optical depth in the ring of $\sim 0.3$. The detailed velocity pattern is similar to that of the nearby arcuate features in Ne II, but at the same time, each of these H$_2$ arcs is observed to extend over $\sim 90^\circ$ and to define closely a ring circulating at $\sim 100$ km s$^{-1}$ with a systemic motion corresponding to $\Pi_{LSR} \approx 40$ km s$^{-1}$. The spatial, kinematic and luminosity-aspect symmetries in the central H$_2$ field thus combine in a straightforward manner to form a simple orderly model of the Galactic nuclear region (as anticipated) whose systemic motion corresponds exactly to the predicted movement of the local standard of rest. It follows that the centre of rest of the Galaxy may now have to be modified, and that large-scale spiral structure may be best understood in terms of some kind of massive outflow from the Galactic nuclear region. Whether this constitutes a new constraint on physical theory remains to be seen.

The broad features of the ionized outflow from the central region of the Galaxy and the radial gradient in temperature seem now to resemble rather closely the conditions observed in some molecular star-forming regions. Thus, examples of the latter indicate high-velocity, ionized flows near the core of the massive molecular outflows whilst many small regions of uniform ‘shocked’ H$_2$ are surprisingly prevalent in the molecular outflow. Here too, according to polarization studies, a disc may be present whilst the emission features may be intrinsic rather than scattered radiation (McLean et al. 1985). Although the analogy is not necessarily reliable, the H$_2$ ring could be most plausibly seen as part of a rapidly cooling, dynamically relaxing, clumpy outflow from the nuclear region into the central disc ($R \leq 50$ pc). Thus, in addition to the difficulties that arise in large-scale Galactic dynamics if $\Pi_{LSR} \approx 40$ km s$^{-1}$, the problems already recognized in explaining molecular outflows in star-forming regions seem to recur, albeit on a much larger scale, in the Galactic centre itself.
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References


