Possible explanations for some unusually large velocity dispersion molecular clouds near the Galactic Centre

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ABSTRACT
Molecular clouds in the Galactic Centre region typically have a velocity dispersion that can be larger by almost a factor of 2 compared with the velocity dispersion of similar mass clouds elsewhere in the Galaxy. However, there are at least two giant molecular clouds, and perhaps as many as half a dozen, located within a kpc of the Galactic Centre that have internal random velocities, observed in 12CO and H I emission lines, that extend from about 0 to almost 200 km s\(^{-1}\). This is larger by a factor of about 10 than normal giant molecular clouds. Two of the most prominent clouds have a molecular mass, estimated from the 12CO emission, of \(10^6\) M\(_\odot\) and their atomic hydrogen mass is about \(2 \times 10^5\) M\(_\odot\). We consider various possible physical mechanisms for the large velocity dispersion of these clouds.

Key words: ISM: clouds – ISM: kinetics and dynamics – ISM: molecules – Galaxy: centre.

1 INTRODUCTION
The Galaxy has several thousand giant molecular clouds (GMCs) of mass \(10^7\) M\(_\odot\) or greater. The internal velocity dispersion of these clouds in the 12CO emission, in almost all cases, is approximately equal to their virial velocity of about 10 km s\(^{-1}\). However, there are at least two very unusual giant molecular clouds, located at \((l, b) = (3.2\degree, 0.3\degree)\) and \((5.4\degree, -0.5\degree)\), which have a velocity width of almost 200 km s\(^{-1}\) that is a factor of \(\sim 10\) larger than their virial velocity (cf. Bitran 1987; Riffert et al. 1997; Boyce & Cohen 1994); see Fig. 1. Hereafter we shall refer to these objects as wide line clouds (WLC). Oort drew attention to the large velocity dispersion of the WLC at 3.2\degree longitude in his influential review article almost two decades ago (Oort 1977). However, these clouds remained largely unexplored until the mid-1980s when Stark & Bania (1986) and Bitran (1987) mapped them at high spatial resolution in 12CO, 13CO, and CS, and confirmed their unusually large velocity dispersion. The observed velocity dispersion (full width at half maximum) even in CS, which is associated with high density cores of clouds, is found to be about 40 km s\(^{-1}\) compared with \(\sim 5\) km s\(^{-1}\) for ordinary giant molecular clouds (Stark & Bania 1986). More recently, Boyce & Cohen (1994) have carried out a survey of the Galactic Centre region in the OH absorption line at 1.67 GHz, and at a resolution of 0.2\degree, and find seven clouds with a velocity dispersion of the order of 100 km s\(^{-1}\). This result provides support for earlier claims of Stacy et al. (1989), which were based on CO observations of the Galactic Centre.

The observational properties of the two most prominent WLCs are discussed in detail in a companion paper (Riffert et al. 1997); the main properties of the WLCs are summarized here for completeness. The angular size of these WLCs is about 0.5\degree. They have well-defined (sharp) boundaries, and appear to be connected to an extended structure which is quite prominent in H I emission. The angular size of these WLCs is about 0.5\degree. They have well-defined (sharp) boundaries, and appear to be connected to an extended structure which is quite prominent in H I emission. The molecular mass of WLCs is estimated to be \(\sim 10^7\) M\(_\odot\) from 12CO emission (Boyce, Cohen & Dent 1989; Stacy et al. 1989), and their atomic hydrogen mass is about \(2 \times 10^5\) M\(_\odot\) (Riffert et al. 1997). However, the molecular mass of the WLCs is perhaps closer to \(10^6\) M\(_\odot\), since the ratio of H\(_2\) to 12CO mass for clouds in the Galactic Centre is likely to be smaller than that of the solar neighbourhood by an order of magnitude.

In this paper we investigate several possible physical mechanisms for the large velocity dispersion of these objects. The organization of this paper is as follows. In the next two sections we give simple physical arguments to constrain the properties of these objects and discuss several possible models for their large velocity dispersion. The main results are summarized in Section 4.

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Figure 1. Longitude–velocity maps of the two most prominent WLCs and three very large GMCs in the disc of the Galaxy, each integrated over its full latitude extent (5° WLC: $-0.625$ to $-0.125$; 3° WLC: $0.125$ to $0.75$; W44: $-3$ to $1$; W51: $-0.625$ to $0$; Cas A: $-4$ to $3$). The mass of each of the three GMCs is in excess of $10^6 M_\odot$, and is similar to the mass of the WLCs. The contour interval in all the maps is $0.4$ K deg, except that one additional contour at $0.2$ K deg has been added to the 5° W map in order to better define the low-intensity ridge at high velocity. Note that the velocity scale is the same for all five maps. In order to make the Galactic plane clouds appear as they would at the Galactic Centre, the longitude scale for each has been compressed relative to that of the WLCs by the factor $d/8.5$, and their latitude-integrated intensities have been reduced by the same factor, where $d$ is the distance to the cloud in kpc (assumed to be 2.9 for W44, 7 for W51, and 4.6 for Cas A). These $^{12}$CO maps, obtained with the 1.2-m telescopes in Cambridge, Massachusetts and on Cerro Tololo, Chile (Bitran 1987; Dame & Thaddeus 1994), were kindly provided to us by Tom Dame and Pat Thaddeus.

2 WHAT CAUSES THE LARGE VELOCITY DISPERSION OF WLCs?

The observed full velocity extent for the two most prominent WLCs is $\sim 200$ km s$^{-1}$, or a factor of about 10 larger than normal giant molecular clouds. Can this large velocity dispersion arise from a chance alignment of molecular clouds along the line of sight? This is the simplest possible model for the WLCs, which will be entirely satisfactory provided that there is a reasonable probability for the chance alignment of about 10 different normal GMCs along the line of sight (and of course we need at least 2, perhaps as
many as 7, such alignments as seen from our location in the Galaxy). These alignments must be almost perfect, so that the projected angular size of the object is about 0.5°, i.e., no greater than the size of a typical GMC near the Galactic Centre, and the clouds should be spatially well-separated in order for their velocity dispersion to add up in projection. The chance alignment probability calculation is described in some detail in the Appendix. The basic idea is to place a total number of \( N \approx 2.5 \times 10^3 \) normal GMCs at random in the Galactic plane and then ask for the probability of finding \( N^* \) GMCs along a given line of sight where \( N^* = 5 \ldots 10 \). If we ignore the details of the superposition of the \( N^* \) clouds in velocity space and consider only their distribution along the line of sight, the probability for \( N^* = 5 \) is \( p_1 = 0.17 \) which is not particularly small. However, according to the observed velocity spread of the WLCs, the superposition has to be approximately uniform over the entire velocity range from zero to the Galactic rotation speed of 200 km s\(^{-1}\). In addition, there are at least two independent lines of sight, i.e., two WLCs, and Stacy et al. (1989) and Boyce & Cohen (1994) have suggested that there are perhaps five other very high velocity dispersion clouds within about 1 kpc of the Galactic Centre that are somewhat weaker versions of the two clouds considered here. Taking these two facts into account, the chance alignment probability reduces to \( 10^{-2} \) for two WLCs and to \( 5 \times 10^{-7} \) for five WLCs. The corresponding calculations are presented in the Appendix, and they also include the effects of an enhanced GMC density in the Galactic Centre region. These results suggest that the WLCs must be spatially localized objects, and we should explain a physical reason for their high velocity dispersion.

The WLCs are also not likely to be tangent points of spiral arms, because in order to achieve the observed \( \sim 200 \) km s\(^{-1}\) velocity extent, we have to be looking at a several-kpc-long straight stretch of a spiral arm along the line of sight. Furthermore, a typical spiral arm is observed to have a sharp edge on one side [in the \( l-v \) (longitude–velocity) map] but is diffuse at the other end extending up to 10° in longitude, and has a velocity width of less than 40 km s\(^{-1}\); in contrast the WLCs are very compact objects with angular size of about 0.5° (see Fig. 1), thus their morphology is unlike that of a tangent point of an extended arm-like structure. Binney et al. (1991) have suggested that large velocity dispersion features in \( l-v \) maps can arise in a barred spiral galaxy, when material distributed along the long straight section of an \( x \) orbit lies along the line of sight to us. This is an attractive possibility. However, the two most prominent WLCs have internal velocities ranging from \( \sim 0 \) to \( \sim 200 \) km s\(^{-1}\), which requires that the length of the straight segment of the \( x \) orbit pointing at us be greater than \( \sim 1 \) kpc. The a priori probability that two such long sections, assumed to be randomly oriented, lie along our line of sight such that their projected angular diameter is \( \sim 0.5° \) is less than 1 per cent.

Can WLCs, like the GMCs, be gravitationally bound? For the WLCs to be gravitationally bound their mass must be about \( 10^5 M_\odot \), where \( d \) is the distance to the cloud divided by the distance to the Galactic Centre (\( d \sim 1 \) according to Riffert et al.). The time required for such an object, moving along a roughly circular orbit about the Galactic Centre, to spiral inward as a result of dynamical friction of the stars in the Galactic bulge and halo, and to fall into the Galactic Centre, is less than \( 10^8 \) yr (Binney & Tremaine 1987). This rather short dynamical time makes it unlikely that we would find several of these objects just before their imminent merger with the Galactic bulge, and none at larger distances where the dynamical time is much greater. Moreover, the internal velocity distribution of WLCs (\( \sim 0 \)–200 km s\(^{-1}\)) is such that it almost fills the rotation curve of the Galaxy. This is possible only if the objects are at a very special location in their orbits such that their orbital velocity projected along the line of sight is approximately half the Galactic rotation speed. At other places in the orbit the observed velocity dispersion will either project outside of the rotation curve or have negative velocity components, which is not seen in either of the two clouds. These considerations make it very unlikely that WLCs are gravitationally bound objects on a roughly circular orbit about the Galactic Centre.

It is also rather unlikely that the internal velocity dispersion of these clouds is caused by some internal energy source that has stirred up the clouds. The reason is simply the enormous amount of required energy: about \( \frac{3}{2} \left( V^2 \right) M \), where \( V \sim 100 \) km s\(^{-1}\) is the velocity dispersion and \( M \) is the cloud mass observed to have this dispersion. The mass of the WLCs is estimated to be at least \( 2 \times 10^5 \) \( M_\odot \) from 21-cm emission (Riffert et al. 1997), and perhaps more like \( \sim 10^6 \) \( M_\odot \). Thus the energy needed to account for the random internal velocity is at least \( 2 \times 10^{52} \) erg, which is equivalent to the energy of about 20 supernovae. Since the expansion velocity of supernovae in the radiative phase falls off as \( (t/10^4 \) yr\()^{-3/4} \times 10^2 \) km s\(^{-1}\), all of these supernovae must have gone off approximately within the last \( 8 \times 10^3 \) yr or less, otherwise the expansion speed drops below 20 km s\(^{-1}\), whereas the fractional mass of the cloud moving with speed less than 20 km s\(^{-1}\) is very small (most of the kinetic energy of the internal motion of the clouds is associated with gas velocities greater than 40 km s\(^{-1}\)). This would require the highly synchronized star formation of (possibly) hundreds of stars of mass greater than 15 \( M_\odot \). Such a rate of star formation and supernovae is much greater than observed in any other GMC. Neither of the two WLCs have much radio continuum emission (Smith et al. 1978), nor do they show radio recombination lines (Lockman 1989), therefore they are not likely to contain more than a few O–B stars at the present. This casts further doubt on the supernova model, and also constrains the possibility that winds from early-type stars have stirred up the cloud. Finally, there is no natural way to understand the peculiar nature of the observed internal velocity distribution of the clouds, which appears to span the Galactic rotation curve in this scenario or any other that appeals to some internal process to enhance the velocity dispersion. Any one of the above arguments is perhaps not compelling by itself to force us to discard either the supernova model or the stellar wind model; however, taken together they make a strong case against these possibilities. It might be tempting to try other
possible energy sources for the WLCs, but they are likely to suffer from many of the same problems as the models described above, i.e. large numbers of objects needed in a small volume to meet the energy requirement, lack of emission at other wavelengths, and the observation that the random internal velocity distribution of WLCs is such that it fills the Galactic rotation curve.

A massive object passing through a molecular cloud can enhance the internal velocity dispersion, as a result of gravitational tidal forcing, by an amount of the order of the virial velocity of the object. For instance, a globular cluster punching through a molecular cloud will increase its velocity dispersion by about 15–20 km s$^{-1}$, and a dwarf galaxy by about 40–50 km s$^{-1}$. Neither of these collisions can, however, explain the velocity dispersion of the WLCs. The induced velocity dispersion can be larger if there is a hydrodynamic interaction between the object and the cloud, but this requires the gas content of the colliding object to be of the order of the WLC mass. The tidal stretching of a cloud in the inner part of the Galaxy, arising from the axisymmetric part of the potential, can enhance its velocity dispersion by about $DQ(r)$, where $D$ is the diameter of the cloud, and $Q(r)$ is the angular rotation speed of the Galaxy. For the WLCs this tidally induced velocity is unlikely to be more than $\sim 20$ km s$^{-1}$.

Can we be looking at an external galaxy in the molecular emission which is not visible optically because of the large extinction toward the Galactic Centre? The radius of such a galaxy at a distance of 0.5 Mpc would be $\sim 2.5$ kpc, its virial mass (determined from the cloud velocity dispersion) $\sim 10^{10}$ M$_\odot$, and it would have a molecular mass of $\sim 10^9$ M$_\odot$ (assuming the standard ratio of H$_2$ to $^{12}$CO mass). This ratio of the molecular to the total mass of the object is rather large, and if it is a disc galaxy it should be seen nearly edge-on in order for the observed velocity dispersion to be $\sim 100$ km s$^{-1}$. However, in such a case the observed aspect ratio of the object should be quite different from 1, whereas the observed aspect ratio of both of the WLCs is close to 1.

We have thus far provided several arguments against dynamical models and models that rely on some internal or external energy source to stir up the WLCs, as well as the improbability of chance alignment causing the large velocity dispersion. We finally consider another possibility, namely that the large velocity dispersion is a result of cloud collisions. The probability of molecular clouds colliding within about 1 kpc of the Galactic centre region, where the density of clouds is quite high, is not small (see Section 3, below). The collision of two molecular clouds will cause the velocity dispersion of the resultant object to be greater than the sum of the velocity dispersions of the individual clouds. The dispersion can increase dramatically if clouds collide with large relative velocity, such as when their orbits intersect at a large angle. The collision model also provides a natural explanation for the observed internal velocity distribution of the WLCs, i.e. the minimum internal velocity projected along the line of sight is $\sim 0$ km s$^{-1}$ and the maximum is approximately the Galactic rotation speed. Moreover, it is also natural that we find WLCs located within about a kpc of the Galactic Centre where the molecular cloud density is higher and thus the probability of cloud collisions is large. We explore this model further in the next section.

3 LARGE VELOCITY DISPERSION CAUSED BY CLOUD COLLISION?

The mass function of molecular clouds in the outer Galaxy is a power law,

$$dN = N_0 \left( \frac{M}{M_0} \right)^{-1.45} d(M/M_0),$$

where $M_0 = M/10^6 M_\odot$ and $N_0$ is a constant that is determined by the total mass in molecular clouds (Dame et al. 1986; Combes 1991). Let us assume that this power-law distribution applies to molecular clouds in the inner kpc of the Galaxy as well. The total molecular mass within 1 kpc is estimated to be $\sim 2 \times 10^8$ M$_\odot$ (Bally et al. 1988; Dame et al. 1987). Substituting this in the above equation we find that there should be about 70 GMCs, with mass greater than $10^6$ M$_\odot$, inside a 1 kpc radius of the Galactic Centre, and their mean separation is expected to be about 200 pc. One of these molecular clouds moving along a highly eccentric orbit will undergo a collision with another GMC in about 5 x $10^7$ yr or 1/5 of the orbital time. Since a typical collision is expected to last for about 10$^8$ yr, even a small fraction of these 70 clouds moving along non-circular orbits will result in a few collision events at any time.

Non-circular orbits can arise when the gravitational field is non-axisymmetric, such as in the case of a barred spiral galaxy, which can perturb the orbits of a few clouds randomly and provide a steady supply of clouds on intersecting orbits; as discussed above, the rate we require for this process is quite low. Various observations indicate the existence of a bar in our Galaxy (e.g. Binney et al. 1991; Blitz & Spergel 1991; Blitz et al. 1993), and so non-circular orbits and a number of cloud collisions are certainly expected in the inner Galaxy. Binney et al. (1991) in fact find that they can fit the observed longitude–velocity distribution of molecular gas in the inner Galaxy (the $l$–$v$ diagram of the $^{12}$CO emission for $2^\circ \leq l \leq 15^\circ$ looks like a parallelogram) by considering non-circular orbits. One possible place to have cloud collision and shock formation is near the Lindblad resonances where closed orbits become self-intersecting (Athanasoula 1991). Binney et al. (1991) considered a rotating bar model with a corotation distance of 2.4±0.5 kpc to explain the observed gas distribution in the inner galaxy. The inner Lindblad resonance in this model is at about 0.7 kpc. It is interesting to note that the two most prominent WLCs are also at a similar distance from the Galactic Centre, however, they lie about 50 pc from the Galactic plane. Cloud collision leading to large velocity dispersion is also possible if some of the clouds are moving along orbits that are significantly inclined to the Galactic plane. A careful investigation of the gas/cloud dynamics in a bar potential is outside the scope of this work; we simply assume from here on that cloud collisions can occur with the desired frequency within the inner kpc of our galaxy, and explore whether this can explain the large velocity dispersion of WLCs.

Molecules are expected to be dissociated when clouds collide at a relative velocity of 50 km s$^{-1}$ or greater (McKee & Draine 1991). However, the time for shocked-gas to cool to $10^5$ K is $\sim v_d/n_0$ yr (see McKee et al. 1987), where $n_0$ is
Density (in cm$^{-3}$) of the unshocked gas and $v_s$ is the shock velocity in units of 10 km s$^{-1}$. Thus it takes only a few years for shocked gas at the density expected of molecular clouds to cool down, and so molecules can reform on a short timescale provided that not all grains are destroyed. The fact that CO emission was observed from the supernova 1987A within a year after it went off (see McCray 1993) lends support to the possibility that molecules can in fact form in a short time after the passage of a strong shock.

Density enhancement in a non-magnetic radiative shock is of the order of the Mach number squared, i.e., $\sim 10^4$ for the WLCs. The density enhancement of the shocked gas, however, is drastically reduced in the presence of even a small magnetic field, being of the order of the Alfvénic Mach number $\sim 20$ for GMCs (cf. Draine & McKee 1993). Thus if the magnetic field in the WLCs is of a strength similar to those of the GMCs then the density of shocked molecular gas is expected to be about an order of magnitude larger than the density of unshocked gas, which is not inconsistent with observations. In fact both of the WLCs appear as bright features in high-density tracer molecular line emissions, such as CS, with a velocity dispersion of the order of 50 km s$^{-1}$, which suggests that the mean number density of molecules in these objects is similar to that found in the cores of GMCs.

For the cloud collision model to work one must show that the internal velocity dispersion of the clouds, after the passage of a shock wave, is approximately equal to the relative velocity of collision. This is obviously not the case if the clouds are treated as homogeneous extended slabs of gas colliding head on; in such a case the internal velocity profile consists of two peaks separated by the shock speed, and the width of each peak is roughly the pre-shock velocity dispersion of the clouds. However, molecular clouds are believed to be highly inhomogeneous fractal objects that consist of dense clumps separated by low density inter-clump gas. Therefore the speed of the shock front must vary significantly across the cloud, leading to a very irregular shock front. An irregular pair of shock fronts is subject to a non-linear bending instability (Vishniac 1994) which, as numerical simulations show, gives rise to highly inhomogeneous filamentary structures even when two homogeneous clouds collide, and this considerably enhances the internal velocity dispersion of the cloud (Klein, McKee & Woods 1995). Furthermore, considerable vorticity is produced in the cloud as a result of misaligned pressure and density gradients as the shock traverses through the cloud (Klein, McKee & Colella 1994) which further increases the velocity dispersion. Finally, Kelvin–Helmholtz instabilities and reflection of the shock at the rear end of the cloud cause the velocity dispersion to increase as well (Klein et al. 1994). Unfortunately it is not yet known if these processes in a colliding cloud can explain the observed velocity dispersion of WLCs. The best numerical simulation carried out to date (Klein et al. 1995) considers a highly idealized case of two identical non-magnetic homogeneous spherical clouds colliding at a relative speed of 10 km s$^{-1}$. The velocity dispersion of post-shock gas in this case is found to be significantly smaller than the collision speed. Magnetic fields in a molecular cloud are likely to make the collision less dissipative and thus can significantly enhance the velocity dispersion of the shocked gas. This possibility needs to be explored by future simulations. We now turn to some observational aspects of cloud collisions.

If collisions occur at large relative speeds, of the order of the Galactic rotation speed (which is required to understand the velocity dispersion of WLCs), then the resulting velocity distribution of the shocked gas should range from $\sim 0$ to the Galactic speed, as observed. Shock heating enhances emission from molecules such as CO, so we expect the shocked gas to be very prominent in $^{12}$CO, as is observed (Fig. 1). The WLCs appear to be connected to high-velocity ridges (Riffert et al. 1997). This might be the result of velocity crowding or perhaps the WLCs are undergoing collision with a molecular ridge.

A fraction of the shock energy, of the order of 10 per cent when shock speed is $\sim 200$ km s$^{-1}$ (Draine 1981), is radiated away in the infrared by dust grains. The resulting IR surface brightness of the WLCs is expected to be $\sim 10^{-3}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ ($5 \times 10^7$ Jy sr$^{-1}$), with the peak emission at a wavelength of about 15 $\mu$m. The mean IR background emission observed in the 12-$\mu$m IRAS band at the angular location of the two WLCs is about $3 \times 10^7$ Jy sr$^{-1}$, so it is not surprising that there is no evidence of any excess IR emission detected at the location of the 3° WLC in the IRAS survey. However, there is a bright source at $(l, b) = (5.8°, -0.4°)$, with surface brightness in 12 $\mu$m of $6 \times 10^7$ Jy sr$^{-1}$. Although this source is close to the WLC at $l=5.4°$, it is not clear whether they are physically associated. The observation of vibrationally excited $H_2$ at $\sim 2$ $\mu$m is a good indicator of shocked molecular gas as well. The detection of these emissions will provide evidence for shock heating and thus help test the cloud collision model of the WLCs.

The abundance of certain molecules such as H$_2$O, HCO$^+$, H$_2$S, SiO, etc., is considerably enhanced by the passage of a shock wave (McKee & Hollenbach 1980), and also molecules are excited to high rotational states. Recently Hüttenmeister et al. (in preparation) have mapped the WLC at $l=3.2°$ in HCO$^+$, CS and SiO (2→1 transition), and find that the velocity dispersion in these lines is similar to that observed in $^{13}$CO, OH and 21 cm. These observations lend some support to the cloud collision model. If the large velocity dispersion of WLCs is a result of cloud collisions, then we expect to see a few cases of cloud collision in which the shock wave has traversed only a fraction of the cloud, in which case the cloud should show a substantial velocity gradient. A giant molecular cloud complex located at $l=1.2°$ consists of two clumps which appear to be physically associated but are moving at different speeds. This may perhaps be an example of an early stage of a cloud collision.

4 SUMMARY

Two giant molecular clouds located at a distance of about 1 kpc from the Galactic Centre are observed to have internal velocity dispersions that extend from about 0 to 200 km s$^{-1}$ in $^{13}$CO and H$^1$ emission lines, and also in OH absorption. Stacy et al. (1989) and Boyce & Cohen (1994) suggest that there are perhaps as many as seven clouds near the Galactic Centre with a velocity dispersion of 50–100 km s$^{-1}$, which is an order of magnitude larger than that of GMCs elsewhere in the Galaxy. The molecular mass of two of the


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most prominent high velocity dispersion features, or WLCs, is estimated to be \( \sim 10^6 M_\odot \) (Bitran 1987; Stacy et al. 1989; Boyce et al. 1989). The \( H_\text{I} \) mass of these clouds is about \( 10^4 M_\odot \) (Riffert et al. 1997).

We have explored various mechanisms for the extraordinary velocity dispersion of these clouds. The simplest possibility is a chance alignment of several ordinary giant molecular clouds along the line of sight. However, we find that the probability for chance alignment of \( \sim 10 \) clouds within a beam of angular width \( 0.5^\circ \), which is what is needed to explain the observed velocity dispersion of the WLCs, is too small to be considered a reasonable explanation (Section 2). The proposal that these features are tangent points of spiral arms, or long straight segments of an \( x \), orbit, has several problems as well (see Section 2). Thus we believe that WLCs are spatially localized or coherent objects.

Another obvious possibility is that these clouds have been stirred up by some internal energy source, such as supernovae or winds from early-type stars. The internal kinetic energy of these clouds is estimated to be at least \( 2 \times 10^{52} \text{erg} \), and could be a factor of 10 larger, so a few tens of supernovae are needed to supply the required energy. These supernovae must have gone off within the last \( 8 \times 10^4 \) yr, otherwise the expansion velocity drops below 20 km s\(^{-1}\). These requirements make the supernova model untenable. The lack of much emission in radio from these clouds places an additional constraint on such a model.

The observed internal velocity distribution of these clouds spans \( \sim 0-200 \) km s\(^{-1}\), i.e. it nearly fills the rotation curve of the Galaxy. This peculiar behaviour, in our opinion, severely restricts the above model and many other proposals.

Given the high density of molecular clouds in the inner \( \sim 1 \) kpc of the Galaxy, with mean separation between GMCs of \( \sim 200 \) pc, the probability that a few clouds are undergoing collision at almost the orbital speed is very high provided that some of the clouds have highly non-circular orbits. Several different observations suggest that the Galaxy has a bar; the \( l-v \) distribution of molecular gas in the inner Galaxy seems to be a consequence of non-circular orbits in a bar potential (Binney et al. 1991). Thus it is expected that some of the clouds in the inner kpc of the Galaxy moving along non-circular orbits undergo collisions resulting in a significant enhancement of their internal velocity dispersions (see Section 3). The collision also enhances emission from CO molecules making the objects quite bright; WLCs are in fact the most prominent features in the \( ^{13}\text{CO} \) \( l-v \) map of the inner Galaxy. The observed line-emission in HCO\(^+\), CS and SiO from the cloud at 3.2\( \mu \)m provides some evidence for shocked gas. Observations of the wide line clouds in \( \sim 2-\mu \text{m} \) vibrational lines of \( \text{H}_2 \), \( \sim 15-\mu \text{m} \) continuum emission from shock heated dust, and emission associated with high rotation states of molecules will help to test the cloud collision model and shed some light on these very peculiar objects.

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REFERENCES


APPENDIX

In this appendix we estimate the probability that the observed WLCs are a result of a chance alignment of \( N^* \) molecular clouds along the line of sight. We first divide the Galactic plane into \( L \) cells (or ‘boxes’), each one having the size of a typical giant molecular cloud. Then we choose an arbitrary line of sight passing through \( K \) such cells, and we have

\[
L \approx K \approx \left( \frac{R}{r_c} \right)^2.
\]

Here \( r_c \) is a typical cloud radius and \( R \) denotes the radius of the solar circle. Next we place at random \( N \) molecular clouds into those \( L \) cells; the number of different possible combinations is \( \approx (L/N) \). Let \( N^* \) be the number of clouds along a given line of sight, then there are \( z^* = (K/N^*) \) possible ways of placing the clouds at random into the \( K \) boxes. The remaining \( N - N^* \) clouds outside the line of sight can
be arranged in $z_e$ different ways where $z_e=(L-K/N-N^*)$. Thus, the probability $p_1$ for a single WLC along a given line of sight is given by

$$p_1 = \frac{I_N}{N^*} \binom{L-K}{N-N^*} \binom{L}{N} \binom{N}{N^*} \binom{N^*}{L-N^*}.$$

The various binomial coefficients in this expression can be approximated by employing Stirling’s formula, i.e.

$$\frac{n!}{m!} \approx \frac{1}{\sqrt{2\pi n}} \exp \left[ m \ln \left( \frac{n}{m} + 1 \right) \right],$$

which is valid for small values of $m/n$. Thus we obtain

$$p_1 \approx \frac{1}{\sqrt{2\pi N^*}} \exp \left[ N^* \ln \left( x + 1 - x \right) \right], \quad (A1)$$

with

$$x = \frac{KN}{L+N^*} \frac{rN}{RN^*}.$$

Note that the conditions $N^* \ll N$ and $K \ll L$ have been assumed in the derivation of this expression. The number of GMCs (clouds with mass $>10^4 M_\odot$) in the Galaxy is estimated to be $N \approx 2.5 \times 10^3$, a typical cloud radius is $r_c \approx 20$ pc, and their velocity width is about 20 km s$^{-1}$ (cf. Dame et al. 1986); however, clouds in the Galactic Centre region have larger velocity dispersions, typically 40 km s$^{-1}$ (see Combes 1991). Thus, in the inner 1 kpc we need about five clouds ($N^* = 5$) along the line of sight to explain the 200 km s$^{-1}$ velocity extent of the WLCs, and outside this region approximately 10 clouds are required ($N^* = 10$). Taking $R = 8.5$ kpc we find from equation (A1) $p_1 = 0.038$ for $N^* = 10$ and $p_1 = 0.17$ for $N^* = 5$.

The probability $p_1$ calculated above is based on the assumption that the $N^*$ clouds are randomly distributed along the line of sight. However, the observations of WLCs suggest that the clouds along the line of sight should be distributed such that the superposition of the internal velocity dispersions of the $N^*$ clouds spreads over the entire velocity range from approximately zero to the Galactic rotation speed. Thus we need to revise our estimate of probability for chance alignment to include the constraint on the cloud distribution in velocity space. A cloud in the Galactic plane at longitude $l$ and distance $r$ from the Galactic Centre will be observed at velocity

$$V_{\text{LSR}} = R \sin \left( \frac{V(r)}{r} \right) \frac{V(R)}{R}, \quad (A2)$$

where $V(r)$ is the Galactic rotation speed, and $r$ can be expressed in terms of the distance $d$ to the observer,

$$r = \sqrt{d^2 - 2dR \cos l + R^2}, \quad (A3)$$

where $0 \leq d \leq 2R \cos l$. Now, in order to account for the observed velocity spread we consider distributing the $N^*$ clouds uniformly in velocity space, i.e., we take $N^*$ velocity bins of equal width

$$\Delta V \approx \frac{V_M}{N^*},$$

and place one cloud in each bin. Here $V_M$ is the maximum of the cloud’s internal velocity distribution (the minimum is about zero),

$$V_M \approx V_{\text{LSR}}(\pi - R \sin l) = V(R \sin l) - V(R) \sin l.$$

If we identify $\Delta V$ with the internal velocity dispersion of an individual giant molecular cloud then the superposition of $N^*$ clouds will produce a velocity spread from zero to $V_M$. According to equations (A2) and (A3), each velocity bin can be converted into a distance interval $\Delta d_n = d_n - d_{n-1}$, where $d_n$ follows from those equations inserting $V_{\text{LSR}} = n\Delta V$. Within each interval there are $M_n$ possible ways of placing a single cloud,

$$M_n = 2 \frac{\Delta d_n}{r_c} = 2K \frac{\Delta d_n}{R},$$

where the factor 2 takes into account that $V_{\text{LSR}}$ is a double-valued function of $d$. Then the total number of different combinations for the $N^*$ clouds is given by

$$z^* = \prod_{n=1}^{N^*} M_n = (2K)^{N^*} \prod_{n=1}^{N^*} \frac{\Delta d_n}{R}.$$

Using this expression, we obtain the corrected chance-alignment probability for a single WLC along a given line of sight,

$$\hat{p}_1(l, N^*) = \exp \left[ N^* \ln (2\pi N^*) - xN^* + \prod_{n=1}^{N^*} \frac{\Delta d_n}{R} \right], \quad (A4)$$

The calculation of probability requires as input the Galactic rotation function $V(r)$, which we approximate as a linear velocity profile for the inner parts of the Galaxy ($r < a = 500$ pc) and a constant velocity $V(r) = V_s \approx 200$ km s$^{-1}$ elsewhere. In this case, all clouds placed inside the radius $a$ have the same Doppler shift (see equation A2), and thus their velocity widths do not add up in the projection along the line of sight. Assuming a constant velocity profile through the entire Galaxy leads to an overestimate of the probability, although it considerably simplifies the calculation. Substituting $V(r) = V_c$ into equations (A2) and (A3), we obtain

$$\frac{d_n}{R} = \frac{\cos l - \sin l}{\sin l + \sin a} \sqrt{1 - (\sin l/a_c^2)},$$

where $a_c = (1 - \sin l) n/N^*$. Applying equation (A4) to a WLC at $l = 5^\circ$ we get the corrected probabilities $\hat{p}_1 = 1.3 \times 10^{-4}$ and $\hat{p}_1 = 0.023$ for $N^* = 10$ and $N^* = 5$, respectively.

The above expression for $\hat{p}_1$ (equation A4) denotes the chance alignment probability for a single given line of sight. We now calculate the probability $P_J$ of having $J$ such alignments out of $N_l$ independent lines of sight. The probability $P_j$ of having a single WLC along a longitude $l_i$ is given by equation (A4), i.e., $P_j = \hat{p}_1(l_i, N^*)$. The probability for $J$ WLCs along all possible lines of sight is
where
\[ c_N = \prod_{i=1}^{N_i} (1 - P_i) \quad \text{and} \quad Q_x = \frac{P_x}{1 - P_x}. \]

The above multiple sum can be converted into sums containing powers of \( Q_x \),

\[ S_x = \sum_{\pi=1}^{N_i} (Q_x)^\pi, \]

and we get

\[ W_x = c_N \sum (1 - x)^{J - \sigma} \frac{\prod_{k=1}^{J} S_k^{\mu_k}}{\Pi_{k=1}^{J} \mu_k ! k^{\mu_k}}, \quad (A5) \]

where \( \sigma = \sum_{k=1}^{J} \mu_k \). The integer numbers \( \mu_k \) are obtained as a solution of the equation

\[ \sum_{k=1}^{J} k \mu_k = J, \]

and the sum in equation (A5) extends over all distinct solutions of this relation.

In order to estimate the number of independent lines of sight, we note that only for small values of \( \sin l \) is the velocity spread \( V_m \) due to the superposition of \( N^* \) clouds close to the Galactic rotation speed \( V_0 \). If we require \( V_m V_0 / V_0 > 0.7 \) in order to identify the observed object as a WLC, then \( |\sin l| < 0.3 \) which leads to a possible longitude range of about 35° around the Galactic Centre. Since the angular extent of a typical WLC is about 0.5°, we obtain approximately 70 independent lines of sight (i.e., \( N_i = 70 \)). From equation (A5) we then calculate the probabilities for \( J = 1 \) (one WLC in the Galaxy) to be 0.13, for \( J = 2 \) to be \( 1.0 \times 10^{-2} \) and for \( J = 5 \) to be \( 4.7 \times 10^{-7} \).