DYNAMICS OF THE GALACTIC BULGE FROM GAS MOTIONS

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ABSTRACT: Observations of cold gas in the inner galactic disk show a clumpy, highly asymmetric distribution, with large non-circular velocities. Recent work has shown that the flow of gas in the inner few kpc is dominated by a rapidly rotating bar, with corotation at $R \simeq 2.4$ kpc and oriented at an angle of $\theta_{\rm incl} = 16 \pm 2^\circ$ with the line-of-sight to the Galactic Center. From the kinematical model the gravitational potential in the inner Galaxy can be determined. Gas falls inwards through the bar's inner Lindblad resonance at a rate of $\sim 0.1\,M_\odot/\,yr$; this suggests that in episodic star formation significant mass and angular momentum may be added to the inner bulge.

1. Cold Gas in the Inner Galaxy

The central 500 pc of the Galaxy contain of order 3% of the total Galactic luminous mass, 3% of the cold gas component, and 10% of all starforming activity (e.g., Güsten 1989). Only a small fraction of the cold gas in the Galactic Center (GC) region is in the form of neutral HI, measured at 21 cm (Burton & Liszt 1978, 1983; Sinha 1979; Braunsfurth & Rohlfs 1981); the total HI mass inside ~ 1.5 kpc is $1 \times 10^7\,M_\odot$. The dominant component is the cold molecular gas observed in mm-emission lines of molecules such as ^{12}CO, ^{13}CO, CS (Bania 1977, Sanders *et al.* 1984, Heiligman 1987, Dame *et al.* 1987, Bally *et al.* 1988). The inferred gas densities range from $\sim 200\,{\rm cm}^{-3}$ to $\sim 3 \times 10^4\,{\rm cm}^{-3}$, the total mass is $\sim 10^8\,M_\odot$, and the surface density of the inner layer is $\sim 300\,M_\odot/\,{\rm pc}^2$.

It has long been known that the distribution of the cold gas in the (l, v)-diagram is not well described by models in which gas moves on circular orbits in an axisymmetric potential. At least four aspects support this view:

(i) Its clumpiness: mm-observations detect structure from the smallest resolved scales ($\sim 1' \sim 3$ pc) to objects like Sgr B, with a mass $\simeq 5 \times 10^6\,M_\odot$

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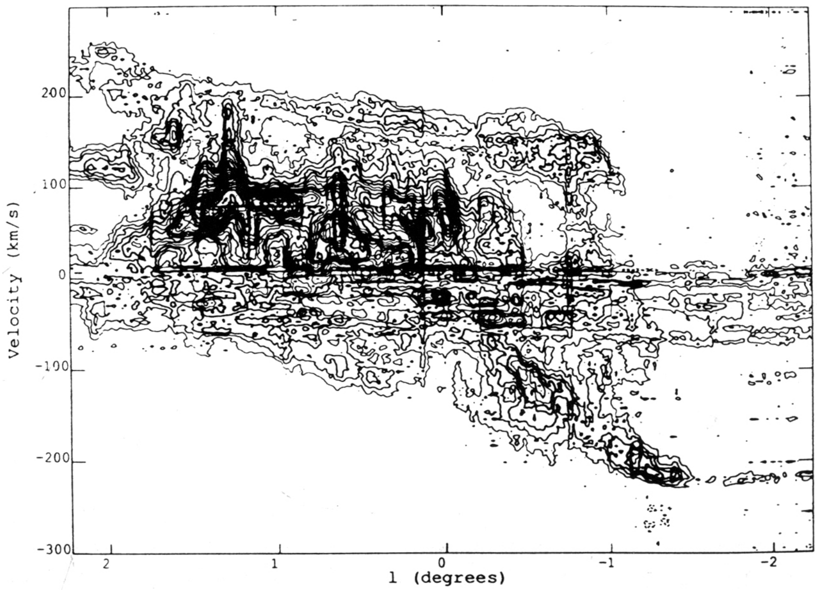

Figure 1. (l, v) digram of ^{12}CO $J = 1 \rightarrow 0$ averaged over $|b| < 0.1°$. The contours (spaced at intervals of 1 K) show a striking parallelogram. (From Binney *et al.* 1991).

(Stark *et al.* 1991). About one third of the GC molecular gas is in such giant cloud complexes (Bally *et al.* 1988; henceforth B88).

(ii) Its asymmetry: About three quarters of the ^{13}CO and CS emission come from positive longitudes and three quarters from material at positive velocities (B88). Part of the longitude asymmetry can be explained as a perspective effect (see below), and part of both asymmetries is caused by the one-sided distribution of the small number of giant cloud complexes. However, an additional overall asymmetry of either hydrodynamic or gravitational origin may be indicated.

(iii) Out-of-plane material: Only about 70% of the GC molecular gas appears to have settled to an equilibrium configuration in the Galactic plane (B88). According to Liszt & Burton (1980), most aspects of the HI distribution somewhat further out can be modelled in terms of *inclined* (by $\sim 13°$) elliptical streamlines. Whether a similar but weaker tilt can be seen in some of the molecular gas is controversial (Heiligman 1987, B88).

(iv) Non-circular and 'forbidden' motions: Known for a long time, these are perhaps most clearly seen in the 'molecular parallelogram' in the (l, v) diagram of Fig. 1 (reproduced from Binney *et al.* 1991). Essentially, the deviations from circular velocities in this structure are as large as the alleged circular velocities themselves. As many papers have noted, either expansion involving large (perhaps improbable) amounts of energy, or a non-axisymmetric potential, is required to generate the observed velocities.

2. Kinematic Model of Galactic Center Gas

Recently, Binney, Gerhard, Stark, Bally & Uchida (1991) have argued that the complex distribution and kinematics of cold gas in the GC can best be understood in terms of motions in a rapidly rotating barred potential. The key to the Binney *et al.* model is the 'molecular parallelogram' referred to above, with its strikingly vertical edges in the (l, v)-diagram. We argue that this feature arises from gas on a narrow range of closed orbits in a rotating barred potential.

Given the extreme inhomogeneity of the ISM and its wide range of scales, it is not immediately clear whether hydrodynamic modelling should concentrate on the ISM's particle nature, or on its smooth fluid aspects – see Binney & Gerhard (1992). However, all hydrodynamic simulations of gas flows in gravitational potentials, using either sticky particles (Schwarz 1981, 1984; Habe & Ikeuchi 1985) or smooth fluids (Sanders & Huntley 1976; van Albada 1985; Mulder & Liem 1986; Athanassoula 1992), show that, if a quasi-equilibrium flow is established, it is generally a good approximation to think of such a flow in terms of the closed ballistic orbits in the underlying gravitational potential. Only near resonances or where closed orbits intersect, do hydrodynamic forces significantly change this picture.

In a barred potential, gas inside corotation follows the main prograde x_1 family until these orbits becomes self-intersecting near the inner Lindblad resonance (ILR). When the inflowing gas reaches the highest-energy self-intersecting x_1-orbit (the 'cusped orbit' in Fig. 2), the hydrodynamic simlations show that a shock forms, which causes it to switch to the closed 'x_2' orbits – another prograde family lying deeper in the potential well, but elongated along the short axis of the potential. Essentially, gas reaching pericentre on the 'cusped' orbit crashes into gas at apocentre on the largest embedded x_2 orbit, producing a spray of material, which in turn causes a shock at the far side of the 'cusped' orbit. From there, material drifts through steadily deeper-lying x_2 orbits, which are not affected by the shock. It is this shock which Binney *et al.* argue gives rise to the observed parallelogram.

The sequence of closed x_1 and x_2 orbits and their projection into the (l, v)-diagram for an observer near the long axis of a rotating bar is shown in Fig. 2. Requiring that the (l, v) trace of the 'cusped' orbit resemble the observed parallelogram determines that observers near the Sun must view the GC bar at a narrowly constrained angle around $\theta_{\rm incl} = 16°$. By contrast, only a weak limit on the bar's axial ratio q can be obtained, as this does not influence the orbit shapes near the ILR much. If we model the inner density distribution as a prolate ellipsoid, then $q \gtrsim 0.75$.

With the same viewing angle, it is also possible to account for the rapid fall-off in the HI terminal velocity observed near $l = 2°$ and the subsequent slower decline out to $l = 12°$. For a given scale of the parallelogram and bulge mass profile, the HI data determine the pattern speed of the bar such

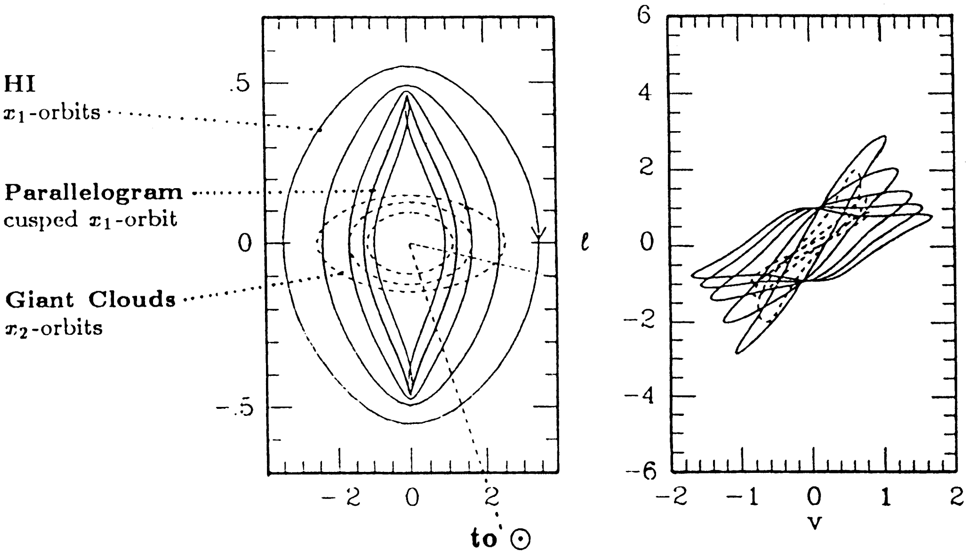

Figure 2. Closed orbits in a rotating barred potential and their projection into the (l, v)-diagram for an observer near the long axis of the bar. (From Gerhard 1992, after Binney *et al.* 1991).

that corotation is at $R_{\rm corot} \simeq 2.4 \pm 0.4$ kpc. In the region $R \lesssim 1.2$ kpc, where the HI terminal-velocity curve decreases outwards, the circular velocity is, in fact, rising.

The strong points of the Binney *et al.* model are that it can fit the (l, v) distribution and the associated large non-circular motions of the molecular parallelogram and the HI terminal curve. Further, that it predicts a perspective asymmetry in the gas distribution which goes in the same sense as that observed, and in the sense expected from the bulge infrared photometry (Blitz & Spergel 1991, COBE). The model naturally accounts for the absence of cold gas between $R \sim 1.5$ kpc and $R \sim 3.5$ kpc, since in the neighbourhood of corotation no stable closed orbits exist on which cold gas could settle. The molecular ring at $R \sim 3.5$ kpc may be associated with gas accumulating near the bar's outer Lindblad resonance. Finally, the giant molecular clouds at the GC, such as Sgr B and Sgr C, are observed in the region of the (l, v)-diagram predicted to be occupied by x_2-orbits inside the ILR .

However, it also appears that some essential ingredients are still missing from the model. On the one hand, the observed lopsidedness of the GC molecular gas is probably too great to be accounted for just in terms of perspective effects, and it remains to be demonstrated whether these can be supplemented and enhanced by hydrodynamic clumping when the self-gravity of the gas is included. The interpretation of the molecular parallelogram in terms of the transition from x_1 to x_2 orbits is only qualitatively born out by simple particle-hydrodynamic simulations (Jenkins 1991); this

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issue may also be connected with the choice of 'correct' description for the interstellar gas. Finally, there is no explanation yet for the three-dimensional gas motions, in particular the tilt in the HI gas distribution. While gas dynamical simulations show that some gas in peanut-bulge potentials may settle on non-planar closed orbits (Friedli & Benz 1992, Friedli & Udry, this conference), no obvious explanation of the HI tilt has yet emerged.

3. The Gravitational Potential in the Galactic Bulge Region

The model of the Galactic Center HI and molecular gas kinematics just summarized assumed a rotating prolate mass distribution with axis ratio 0.75 and density profile (Binney *et al.* 1991)

$$\rho(a) = 53 \left(\frac{a}{100\,\mathrm{pc}}\right)^{-1.75} \mathrm{M}_\odot\,\mathrm{pc}^{-3}, \tag{1}$$

rotating with a pattern speed of $\omega_p = 63\,\mathrm{km\,s^{-1}\,kpc^{-1}}$. Here a is a prolate-spheroidal radius. As the gravitational potential in the inner Galaxy may arise from a superposition of several components, it may be useful to specify the monopole and quadrupole parts in the kinematic model separately. The spherical part of the density in eq. (1) is (Gerhard 1992)

$$\rho_0(r) = \rho_s \left(\frac{r}{r_s}\right)^{-7/4} = 37 \left(\frac{r}{100\,\mathrm{pc}}\right)^{-7/4} \frac{\mathrm{M}_\odot}{\mathrm{pc}^3}, \tag{2}$$

corresponding (up to an additivive constant) to the potential

$$\Phi_0(r) = \frac{64\pi}{5} G\rho_s r_s^2 \left(\frac{r}{r_s}\right)^{1/4} = 6.4 \times 10^4 \left(\frac{\mathrm{km}}{\mathrm{s}}\right)^2 \left(\frac{r}{100\,\mathrm{pc}}\right)^{1/4}. \tag{3}$$

This spherically averaged density profile is in very good agreement with that derived recently by Kent (1992). He constructed an oblate-isotropic model of the inner bulge, which is based on InfraRed Telescope photometry from the Spacelab Shuttle mission (Kent *et al.* 1992). With a density normalisation of $41.5\,\mathrm{M}_\odot/\,\mathrm{pc}^3$ and a slightly different exponent of 1.85 in eq. (1), this model accounts for a variety of *stellar* kinematics in the bulge.

From the IRT photometry, the inner bulge has ellipticity $\epsilon = 0.39$. If one assumes an oblate-spheroidal mass distribution, such flattening increases the circular velocity by a factor of 1.09 over that in the spherical model with the same spherically averaged $\rho_0(r)$ (Binney & Tremaine 1987; eq. (2-91)). Thus in the plane we expect

$$v_c(R) = 1.09 \left(\frac{16\pi}{5} G\rho_s r_s^2\right)^{1/2} \left(\frac{R}{r_s}\right)^{1/8} = 137 \left(\frac{R}{100\,\mathrm{pc}}\right)^{1/8} \frac{\mathrm{km}}{\mathrm{s}}. \tag{4}$$

Because the fit of the GC bar model to the kinematic data is not sensitive to the bar's axis ratio, the amplitude of the quadrupole term in the plane is uncertain. For the rotating density distribution of eq. (1) it is

$$\Phi_2 \sim -1000 \left(\frac{\mathrm{km}}{\mathrm{s}}\right)^2 \left(\frac{r}{100\,\mathrm{pc}}\right)^{1/4} \cos\left[2(\phi - \phi_0 - \omega_p t)\right], \tag{5}$$

where the pattern speed is $\omega_p = 63\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ and $\phi_0 = 16^\circ$ at the present time, $t = 0$.

One question that still needs to be answered is whether the dominant part of the quadrupole potential measured in the gas motions comes from the inner bulge or disk. Recent COBE near-infrared observations show several qualitative features predicted by Blitz & Spergel (1991) on the basis of earlier 2.4 μ data of Matsumoto *et al.* (1982), suggesting a bar-like triaxial shape for the Galactic bulge. Also several observations of tracer populations have shown asymmetries in l with respect to the Sun-Galactic Center line, consistent with a barred distribution with its nearer end at $l > 0$ (Nakada *et al.* 1991, Whitelock & Catchpole 1992).

However, the large figure rotation rate ($R_{\mathrm{corot}} \simeq 2.4\,\mathrm{kpc}$) inferred by Binney *et al.* from the gas motions may suggest that the rapidly rotating component is more akin to a (possibly thick) disk-like bar than to a triaxial bulge-spheroid. For example, the peanut bulge of NGC 4565 has an estimated minimum corotation radius of $\sim 15\,\mathrm{kpc}$ (Gerhard & Vietri 1986). It is not known whether the inner stellar disk of the Galaxy is barred. However, while the mass fraction of cold gas in the inner 500 pc is only $\sim 5\%$ and it therefore does not substantially influence the azimuthally averaged rotation curve, it may nevertheless make a significant contribution to the potential's quadrupole moment, because it is flattened to the plane and moves on highly elongated orbits. Based on observations of external barred galaxies (e.g., Kormendy 1982) it would not be surprising if the gravitational potential in the inner Galaxy were made up of non-trivial contributions from several components.

4. Gas Infall and Bulge Evolution

In this rapidly rotating barred potential, molecular gas is moving inwards through the shock associated with the cusped orbit. We may roughly estimate the mass inflow time-scale by noting that the gas cannot stay on the cusped orbit for much more than one dynamical time, 2×10^7 yr. The mass in the parallelogram has been estimated to be $\sim 2 \times 10^6\,\mathrm{M}_\odot$ (Bania 1977), so the the mass inflow rate through the ILR is approximately $0.1\,\mathrm{M}_\odot/$ yr.

Whether or not the gas then settles on the inner x_2-orbits, its highly clumped nature must lead to further angular momentum loss to the stars in the bulge/bar. Since the orbital speed of the clouds on x_2 orbits is

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faster than the pattern velocity of the bar, orbital angular momentum is lost (i) by gravitational torques from the rotating quadrupole, and (ii) by *dynamical friction* against the bulge stars. The latter process occurs because the clouds are very massive, and it alone causes gas inflow to yet smaller radii at a rate comparable to that estimated above (Stark *et al.* 1991). Thus the present population of Galactic centre clouds must be transient, and for the next Gyr material will be accreting onto the GC at an average rate of $\sim 0.01 - 0.1\,M_{\odot}/\,yr$.

An accretion rate of $0.1\,M_{\odot}/\,yr$, if typical, would amount to of order one third of the total bulge mass inside 500 pc over a Hubble time. Since the typical circular velocity in the bulge is $\sim 180\,km\,s^{-1}$ and the internal streaming velocity in the oblate-isotropic case is only $\sim 65\,km\,s^{-1}$ (estimated from Kent's model, 1992), such continuous accretion would also transfer to the bulge stars much of their present angular momentum content. While some of this angular momentum may be transported outwards again, in winds or through the rotating barred potential, some fraction may remain locked in internal streaming motions.

These would be remarkable consequences. On their way to the Galactic Center, the GC clouds are presumably making stars. As they sink in the potential well, they may then dump their remaining mass onto the GC, causing a period of enhanced star formation. One may speculate that, integrated over the age of the Galaxy, a significant part of the stellar mass in the inner bulge region might have been formed in this way, and perhaps been scattered out of the galactic plane into the bulge by the vertical instability processes discussed by Combes *et al.* (1990) and Raha *et al.* (1991). The agent for these processes is a rotating bar, which either scatters resonant stars out of the plane or becomes itself unstable to a bending mode. Not enough is yet known about these processes to say whether they can occur continually or periodically, and how they interact with the expected gas flow patterns in the disk.

There is some evidence for an intermediate-age metal rich population in the Galactic bulge (e.g., Harmon & Gilmore 1988), and also for dissipative mechanisms in the formation of the bulge (Rich 1990; Minniti *et al.* 1992): these authors show that the velocity dispersion of K-giants in some bulge fields is higher for metal-poor stars than for metal-rich stars. But even the metal-richer stars have ages of at least 5 Gyr, so this part of the Galactic bulge cannot have been formed recently.

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