Archer of the Galactic disk?
The effect on the outer H I disk of the Milky Way of collisional encounters with the Sagittarius dwarf galaxy

R. A. Ibata* and A. O. Razoumov

Department of Physics & Astronomy, University of British Columbia, 2219 Main Mall, Vancouver, B.C., V6T 1Z4, Canada
Electronic mail: surname@astro.ubc.ca

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Abstract. Hydrodynamical calculations undertaken to simulate the collisional interaction between the Sagittarius dwarf and the Galactic outer H I disk are presented, constrained by recently derived orbital and mass parameters for this dwarf galaxy. It is found that a significant distortion to the structure of the Galactic H I disk will be induced by the collision if the mass of the dwarf exceeds \( \sim 10^9 \) M\(_\odot\); this value is consistent with an estimate derived by requiring that the dwarf galaxy is sufficiently robust to survive tidal disruption until the present time. Though the precise details of the interaction are compromised in our simulations by the lack of a live Galactic halo, we find that for model masses \( \gtrsim 5 \times 10^9 \) M\(_\odot\), prominent spiral arms and a substantial lopsidedness in the outer disk are produced. Furthermore, a noticeable warp-like structure is induced in the disk. Thus the Sagittarius dwarf may have significantly affected the star formation history and structure of the outer Galaxy. These simulations confirm the possibility of determining the current merging rate of low surface brightness, gas-poor dwarf galaxies of mass \( \gtrsim 10^9 \) M\(_\odot\) onto giant spiral galaxies from careful analysis of observations of the structure of H I disks.

Key words: Galactic dynamics – interstellar medium – Sagittarius dwarf galaxy

1. Introduction

The observed warps of spiral galaxies are commonly believed to be either caused by the torque due to a misalignment of the outer halo and the disk, or to be the natural oscillatory response of the gas layer to small perturbations (Binney 1992). However, recent numerical simulations have shown that, in models with realistic disk to halo mass ratios, disks placed inside oblate halos align themselves with the plane of symmetry of the halo within a few orbital periods (Dubinski & Kuijken 1995). So in both scenarios it seems likely that perturbers are required to maintain the warps.

The influence of specific perturbers on the disk of the Milky Way has been considered. Weinberg (1995) put forward a model where disk modes are being excited by the joint torque from the Magellanic Clouds and the halo. Another possible perturber of the Galactic disk is the Sagittarius dwarf galaxy (Ibata et al. 1994; Ibata 1994), which likely collides with the Galactic disk every \( \sim 1 \) Gyr (Ibata et al. 1997, hereafter IWGIS). This intriguing possibility was brought to attention by Lin (1996), who realized that the position where one of the likely orbits (given the initial kinematic data of Ibata et al. 1994) last passed through the Galactic disk is coincident with the position where the maximum displacement of the H I warp would have been at that time.

Lin modeled the Galactic H I gas with 4000 massless and collisionless tracer particles placed in circular orbits in a fixed Galactic potential. The response of these particles to the passage of a (collisionless) point-mass particle on the...
orbit deduced for the Sagittarius dwarf was then analyzed. He found that, if the Sagittarius dwarf has a mass of at least \(5 \times 10^9 M_\odot\), and moves on an orbit which fit best the then extant data, then the resulting perturbation to the modeled disk, when evolved up to the present time, looked similar to the observed warped distribution of H I in the outer Galactic disk.

However, by choosing massless particles as tracers of the Galactic H I disk, the Lin (1996) study did not model the nature of that Galactic component, which of course is both self-gravitating and gaseous. Furthermore, an analysis of recent data (IWGIS) supports orbits with a longer period than that adopted by Lin (1996); the currently best-fit orbit, implies that the Sagittarius dwarf did not collide with the Galactic disk \(\sim 10^8\) years ago, as is required in Lin’s model.

In this paper we present hydrodynamical simulations to analyze the effect that a single passage of the Sagittarius dwarf could have on the gaseous outer disk of the Milky Way. By including in the simulations pressure forces and self-gravity of the gas, and adopting the orbit determined from recent observations, we model this interaction much more accurately. More than \(\sim 10\) collisions with the Galactic disk are predicted to have occurred over the \(\gtrsim 10^8\) Gyr lifetime of the dwarf (IWGIS); however, due to the effect of dynamical friction during tidal disruption, one cannot estimate accurately the position and velocity, or even the peri- and apo-Galactic distances, that the Sagittarius dwarf had \(10^8\) Gyr ago. We therefore restrict ourselves in the present contribution to the consideration of the effect of a single encounter with the Galactic disk; for concreteness, we will study the aftermath of the collision due to occur \(\sim 25\) Myr from the present time on the opposite side of the Milky Way from the Sun.

2. The Sagittarius dwarf: its orbit and mass

A comprehensive review of the current observational constraints on the nature of the Sagittarius dwarf spheroidal is given in IWGIS. However, for the present study, only its orbit and its mass are important.

The distance to the center of mass is \(25 \pm 1\) kpc (Ibata et al. 1994, Mateo et al. 1995), while the radial velocity of the center of mass in a galaxy-centered non-rotating reference frame is \(171 \pm 1\) km s\(^{-1}\) (IWGIS). Several numerical studies (Oh et al. 1995, Piatek & Prior 1995, Johnston et al. 1995, Velazquez & White 1995) have shown that low mass, initially spherical stellar bodies such as dwarf spheroidal galaxies become elongated in the tidal field of the Milky Way, such that the elongation aligns along the direction of motion. This empirical finding is only approximately true, since in the numerical models, the leading arm of disrupted particles tends to be nearer to the Galactic center than the lagging arm (see e.g. Piatek & Prior 1995, their Figure 1). However, we are fortunate to observe the Sagittarius dwarf from a position which is almost directly opposite the Galactic center to its present position, so that its elongation will in fact be aligned with its proper motion vector to very good approximation. The major axis of the Sagittarius dwarf is approximately parallel to the Galactic coordinate line \(l = 5^\circ\) (IWGIS), implying an essentially polar orbit. Combining these constraints, together with a preliminary measurement of the proper motion (\(2.1 \pm 0.7\) mas/yr towards the Galactic plane; Irwin et al. 1996, IWGIS), allows one to fit an orbit for the dwarf in an assumed Galactic potential. The Galactic potential used to determine the orbit is identical to that detailed below in Section 3; the center of mass orbit whose distance and projected velocity best match the observations is presented in Figure 1.

The mass \(M_{SG}\) of the Sagittarius dwarf is a puzzling quantity. One may determine a first estimate of its mass by applying the virial theorem: an object with radial velocity dispersion \(11.4 \pm 0.7\) km s\(^{-1}\) (IWGIS) and a characteristic major axis diameter \(\sim 9.6\) kpc (IWGIS) has a virial mass of \(\sim 1.5 \times 10^8 M_\odot\) (note that we have used the major axis length in this calculation, which is likely to give an overestimate of the virial mass). However, as shown by Velasquez & White (1995) and Johnston et al. (1995), who specifically modeled the Sagittarius dwarf, such an extended, low mass object is very fragile, and would have been destroyed by Galactic tides long before the present time. This dilemma may be solved if the Sagittarius dwarf has a substantial dark halo, with mass \(\gtrsim 10^9 M_\odot\) (IWGIS); the low stellar velocity dispersion given this high mass can be explained by a radially increasing mass to light ratio.

3. Modeling the interaction

3.1. Order-of-magnitude estimates

We start by illustrating the effect of the passage of the dwarf galaxy through a thin gaseous disk using analytical order-of-magnitude arguments. Neglecting gas dynamics, we can write the momentum transferred to the volume element of the disk as

\[
p \sim \frac{GM_{SG} \rho}{r^2} \cdot \frac{r}{v} \sim \rho v(r),
\]
The solid line shows the $x-z$ plane of the orbit of a massless test particle that best fits the kinematic data (see IWI GIS for details). The radial period of this orbit is 0.76 Gyr. The dotted line shows the orbit taken for the $5 \times 10^9 M_\odot$ model, where dynamical friction has been included in the calculations. Both models have been integrated for 1 Gyr. The ‘star’ symbol represents the present position of the Sun, while the open ellipse (drawn to scale) gives the present position of the Sagittarius dwarf spheroidal.

where $M_{SG}$ and $v$ are the mass and impact velocity of the dwarf galaxy and $r$ is the distance of the disk element from the place of impact. After the collision, the gas element acquires velocity $u(r) \leq v$ which should bring it to some elevation $h$ above the disk. Assuming the model of the Galactic halo potential described below, the vertical gradient of the potential at the point of impact can be approximated well by the relation

$$|\psi_z| \approx C h,$$

where $C \approx 4.4 \times 10^{-32} s^{-2}$. The scale height of the perturbation caused by the dwarf will therefore be

$$h \sim \frac{1}{\sqrt{2C}} \frac{GM_{SG}}{rv}, \quad \text{for } r > R_A,$$

where $R_A = GM_{SG}/v^2$ is the gravitational radius of Bondi-Hoyle accretion. In our scenario the orbital velocity of the dwarf is $v = 365 \text{ km s}^{-1}$. With an extreme case of $M_{SG} = 10^{10} M_\odot$, this model gives a hole $R_A \approx 300 \text{ pc}$ in radius, while material at the edge of this hole is displaced to $h \sim 40 \text{ kpc}$. Since $h \sim r^{-1}$, any disk element with impact parameter, say, $r \sim 3 \text{ kpc}$ can be propelled up to $h \sim 4 \text{ kpc}$ above or beyond the disk. However, this order-of-magnitude estimate lacks essential physics, most importantly dissipation via shocks and subsequent radiative cooling.

3.2. Modeling the H I disk

A more careful treatment is required to predict quantitatively the effect of the collision on the gaseous disk. Walker et al. (1996) presented an N-body simulation to study the interaction of a disk–halo–satellite system in a merger which does not destroy the disk. After such an event, the disk appears to be of an earlier Hubble type than its progenitor, with a substantial amount of heating having been pumped into the disk. This energy will clearly alter the physical state of the gas in the disk resulting in more physical diffusion than in purely N-body simulations. To address this issue, we modeled the H I as a continuous self-gravitating fluid, using a smooth particle hydrodynamics (SPH) tree-code kindly provided by M. Steinmetz (Steinmetz & Müller 1993).

For all of our models of the H I disk, we assume an initially uniform temperature $T_{gas} \sim 100 \text{K}$. We take an exponentially decreasing surface mass density beyond $R = 10 \text{ kpc}$ with scale length 6 kpc (our parameterization of
the data of Burton & te Lintel Hekkert (1986), a Gaussian density distribution in the direction perpendicular to the Galactic plane with a scale height of 500 pc (the measured value at $R = 10$ kpc — Burton (1992)), and a number density of H I at $z = 0$ of 1.0 atoms cm$^{-3}$ (so as to yield the surface mass density at $R = 10$ kpc measured by Burton & te Lintel Hekkert 1986). We chose to set the outer limit of the disk at $R = 25$ kpc. We also chose, for tractability, not to populate the H I disk inside $R = 10$ kpc, to avoid having to simulate the complex interaction of the gaseous disk with the stellar disk. The total mass in H I in the model is then $8.5 \times 10^9 M_\odot$.

Artificial viscosity in the simulation is corrected for shearing, as given by Benz (1990), which would otherwise result in a rapid transfer of mass from the outer to the inner regions of the disk.

One has to make sure that the surface number density of particles in the disk is high enough to resolve the impact area. Our criterion is to have at least 100 particles in the disk impact region corresponding to the size of the dwarf. We therefore chose to populate the annulus representing the H I gas with $3 \times 10^4$ particles whose masses decrease exponentially from $R = 10$ kpc with a scale length of 6 kpc, giving a uniform surface number density.

### 3.3. Cooling of the atomic hydrogen

An appropriate thermal model for the atomic hydrogen is required, so as to mimic the existing temperature and density distributions of the gaseous disk as closely as possible. In nature, the temperature of the gas follows the equilibrium temperature set by the interplay of heating and cooling processes. However, this process is very complex: the cooling rate for a given temperature, density and chemical composition depends on the number density of free electrons, which in turn, depends on the flux of ionizing radiation (from cosmic rays, star formation, supernovae, and so on), which is poorly constrained in the outer regions of the Galaxy. The most problematic issue is that the ISM is likely to be optically thick to radiation in some important emission lines; developing a cooling rate algorithm with the necessary radiative transfer calculations is far beyond the scope of the present contribution.

To make the problem tractable, we instead assume an ISM equilibrium state given by Scheffler & Elsässer (1988), which is based on the local chemical composition and heating rate in the absence of hydrodynamical heating. The settling of the gas onto this equilibrium curve will depend on the amount of dissipational heating, which in our case, is given by the SPH algorithm. The cooling timescale is then just taken from the explicit cooling functions for atomic hydrogen of Scholz & Walters (1991), with the modification that the cooling time may not be longer than $T_{cool} = 10^5$ years. It was found that the results were not sensitive to the choice of this upper bound in the range $10^5 < T_{cool} < 10^6$, in the sense that the configuration of the disk at the end point of the simulations were qualitatively indistinguishable.

### 3.4. The Galactic potential

Ideally, one would prefer to model the Galaxy with a “live” halo, stellar disk, bulge and spheroid. However, the computational resources required for such a treatment are beyond our present capabilities. Instead, the SPH scheme was altered to include a fixed potential for the Milky Way and a moving potential for the dwarf galaxy. The potential of the Milky Way is derived from the mass model of Evans & Jijina (1994). In this model, the disk component, described by a double exponential disk, has radial scale length $h_R = 3.5$ kpc and a Solar neighborhood surface density of $\Sigma_0 = 48 M_\odot/pc^2$. We further assume that the vertical scale length of the disk is $h_z = 0.25$ kpc, and that the density falls to zero at $R = 5 h_R$. The potential corresponding to this density distribution is found by multipole expansion of the Poisson equation using an algorithm described in Englmaier (1997). The halo component is described by a ‘power-law’ halo, so the potential has the following analytical expression:

$$
\Psi = \frac{v_0^2 R_c^2 / \beta}{(R_c^2 + R^2 + z^2 q^{-2})^{3/2}}, \quad \beta \neq 0,
$$

where $R$ and $z$ are Galactocentric cylindrical coordinates, the core radius $R_c = 2$ kpc, $v_0 = 138$ km s$^{-1}$, the exponent $\beta = -0.2$, and the oblateness parameter $q = 1$.

A shortcoming of this approach is that the fixed halo behaves differently to a “live” halo that is free to respond to the passage of the massive dwarf. A “live” halo would respond (in a way that is dependent on the density and kinematics of the halo, and the mass and velocity of the object) to the extra gravitational attraction, leaving a wake of halo material behind the object. This wake would also interact with the H I disk. So, in reality, the interaction of the Sagittarius dwarf with the Galactic disk should be more violent than found here using a fixed halo model.
3.5. Modeling the dwarf galaxy

To obtain a good representation of the dwarf galaxy, one would ideally construct a set of spherical stellar models, evolve them in the Galactic potential for $\sim 10$ Gyr, and choose the model that best reproduces the observations. However, as yet no N-body model has been found that is able to survive Galactic tides and also give a reasonable approximation to the observed distance, radial velocity dispersion and radial velocity gradient. In the absence of such a self-consistent N-body model, we account for the Sagittarius dwarf by including a Plummer sphere potential $\Psi_{SG} = -GM_{SG}/\sqrt{r^2 + r_0^2}$, which progresses along a predetermined orbit. Here $r$ is a radial distance from the guiding center of the orbit, and $r_0 = 1$ kpc. Note that spherical models are not a good representation of the present shape of the Sagittarius dwarf, since it is significantly elongated (axis ratio $3:1:1$; IWGIS), however the difference to the perturbation on the Galactic gas is likely to be small.

For a chosen model mass $M_{SG}$, we calculate the orbit in the above Galactic potential whose projected velocity best fits the kinematic data; dynamical friction is taken into account using the Chandrasekhar dynamical friction formula (see e.g. Binney & Tremaine 1987). So as to minimize the perturbations on the Galactic disk in the initial evolution of the simulation, at the beginning of the integration, the dwarf galaxy models are placed at the position where the center of mass of the model was $4.4 \times 10^8$ years ago.

4. Simulation results

We first followed the evolution of the gaseous disk in the absence of the dwarf. Over the course of a $5$ Gyr integration, the disk was observed to develop small-scale spiral features (high $m$-mode instabilities), but it remained axisymmetric, flat (no simulation particle rose beyond $|z| = 1.5$ kpc), and in particular, it was devoid of large spiral arms (low $m$-mode features).

Two other simulations — all integrated for $1.75$ Gyr — were performed with dwarf galaxy masses $M_{SG} = 10^9$ and $5 \times 10^9 M_{\odot}$. As discussed above, the Sagittarius dwarf should have a mass of $M_{SG} \sim 10^9 M_{\odot}$ to have survived in the Galaxy’s tidal field over its lifetime of $\sim 10$ Gyr. Taking into account that a live Galactic halo will only augment any perturbations to the HI disk, $M_{SG} = 5 \times 10^9 M_{\odot}$ is a reasonable upper limit to be considered. It seems plausible that a more realistic simulation with a time-dependent, inhomogeneous halo able to respond to the passage of a $\sim 2 - 3 \times 10^9 M_{\odot}$ dwarf galaxy, would demonstrate results similar to our fixed-halo $M_{SG} = 5 \times 10^9 M_{\odot}$ simulation.

We now focus on the results of the simulation with $M_{SG} = 5 \times 10^9 M_{\odot}$. Just before the first collision with the dwarf, the disk remains smooth, and only slightly perturbed (the mean level of the outer gaseous disk droops towards the dwarf by $\sim 300$ pc). In Figures 2a and 2b, we display the $x$-$y$ and $y$-$z$ plane structure of the Milky Way’s H I disk just after the encounter at $T = 0.5$ Gyr (i.e. 60 Myr from the present time). The collision produces a plume of ejected particles, seen clearly in Figure 2b. The disk becomes deformed near the point of collision, with vertical displacement that follows approximately the $r^{-1}$ relation predicted by the order of magnitude calculation presented above. Furthermore, on the opposite side of the Galaxy to the point of impact, the HI layer has been pulled down from the Galactic plane by $\sim 1$ kpc due to the attractive influence of the dwarf.

The structure of the disk after 1 Gyr is shown in Figures 2c and 2d. Figure 3 shows the corresponding column density of H I in a Galactocentric annulus of width 1 kpc centered on the point of the collision. At that time, 0.5 Gyr after the collision, the disk is clearly non-axisymmetric: large spiral–like arms dominate the morphology of the outer regions, while the whole disk appears lopsided. The vertical displacement of the gas resembles the observed warp, with main features separated by $\sim 180$ degrees.

The perturbation on the H I disk, it transpires, is a strong function of mass — the effect of the $M_{SG} = 10^9 M_{\odot}$ on the structure of the disk being just noticeable, while the model with $M_{SG} = 5 \times 10^9 M_{\odot}$ produces a noticeable warp-like structure in the disk. The degree of warping depends on the amount of physical and numerical diffusion in the model. In Figure 4 we demonstrate that the adopted equation of state (ideal gas with cooling to an equilibrium state) together with the corrected artificial viscosity, in effect, leads to very little numerical diffusion allowing most of the gas in the plane of the disk to sit at temperatures of $\sim 100$K. There is substantial heating only in disk shocks and tidal tails which follow the dwarf galaxy into the halo, but then this gas cools down to produce two atomic components of the ISM (diffuse and cold phases).

The perturbations induced by the dwarf on the Galactic H I are long-lived, as we show in Figure 5, which displays the configuration of the SPH particles at the end of the $M_{SG} = 5 \times 10^9 M_{\odot}$ simulation, just before the third impact with the Galactic disk. As discussed above, the Sagittarius dwarf has likely had many collisions with the Galactic disk in the past, and will soon crash through the disk yet again. Thus, the outer H I disk may presently be quite disturbed, if the mass of the Sagittarius dwarf is indeed in the range considered here. Once the mass of the dwarf is
Fig. 2. The structure of the H I disk is shown for the $M_{SG} = 5 \times 10^9 M_\odot$ simulation, at simulation times of 0.5 Gyr (just after the collision) and 1 Gyr in the left- and right-hand panels respectively. The coordinate system is inertial, chosen such that the Galactic center lies at the origin and the present position of the Sun is at (-8,0,0). The Galactic plane is viewed from above, so the sense of Galactic rotation is clockwise in the upper panels. The point of impact with the disk is at $x = 22.5$ kpc, $y = 0$ kpc.

better constrained, further simulations, with a live halo, should be performed to obtain a more realistic estimate of the magnitude of these disturbances.

5. Conclusions

Many mechanisms have been proposed to explain the — very common — phenomenon of warps in gaseous disks (see Binney 1992), with perhaps the most reasonable explanation being that warps are simply the natural oscillatory response of the gaseous disk to small perturbations. As such, it is conceivable that the Sagittarius dwarf may provide a perturbing influence which helps to excite periodically the Galactic warp, especially since it seems that warps are transient phenomena and need to be maintained (Binney 1992).

Perhaps most importantly, our simulations show that it is necessary to include the perturbative effect of the Sagittarius dwarf to fully understand the star formation history and spiral structure of the outer Galactic disk. In a subsequent contribution, we will improve on the accuracy of the present simulations by including a live Galactic halo; without accounting for the effects of a real halo, it is probably premature to attempt a detailed comparison of the models to the observed H I distribution.

An interesting prospect is that it may be possible to detect indirectly the presence of dwarf galaxies from their effect on the H I disks of their giant neighbors. For instance, a relatively massive galaxy similar to the Sagittarius
Fig. 3. The column density map (in atoms/cm$^2$) of H I particles in a cylinder with 1 kpc thick walls centered at $R = 22.5$ kpc (the point of impact), as seen from the Galactic center, is displayed. Here, the dwarf galaxy model has mass $M_{SG} = 5 \times 10^9 \, M_\odot$, and the simulation time is 1 Gyr. The angle termed 'Galactocentric longitude' is measured anti-clockwise in the sense of the upper panels of Figure 2; the direction corresponding to the present position of the Sun is $0^\circ$.

dwarf would be extremely hard to detect (due to the very low surface brightness) if it were orbiting an external galaxy at a distance beyond which its brightest giants could be resolved, whereas the effect caused on the structure of its neighbor’s gaseous disk could be readily observable (given a sufficiently high mass). Also, recent numerical simulations (Johnston et al. 1996) suggest that matter disrupted from former dwarf galaxies can form very long-lived streams in the halo of their massive companions. H I disks could also be affected by these structures, depending on their mass density and clumpiness. This may yield a means to quantify the present merging rate (see, e.g., Zaritsky & Rix 1997), a parameter of great value to galaxy formation theory.

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Fig. 4. The number density–temperature diagram corresponding to the simulation displayed in Figures 2a and 2b. At any time during the simulations, the majority of particles stay at low temperatures in the lower left corner of the diagram. A minor portion of the material is being constantly heated through dissipational processes. The heated gas is forced to cool down (see details in the text) to the equilibrium curve which is in turn separated into a cold ($\log T \sim 1.8$) and warm ($\log T \sim 3.8$) component, as expected. Ideally, one would like to mimic the density map of the ISM, comparing models to the observed mass distribution inside dense clouds and in the form of diffuse gas. (Note that the particles displayed in the plot have variable masses.)

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Fig. 5. As Figure 2, but at the simulation time 1.75 Gyr, just before a third collision of the dwarf with the Galaxy. The disturbances clearly remain prominent for longer than the period between collisions.