Are Complex A and the Orphan Stream related?

Shoko Jin* & D. Lynden-Bell
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, U. K.

ABSTRACT
We consider the possibility that the Galactic neutral hydrogen stream Complex A and the stellar Orphan stream are related, and use this hypothesis to determine possible distances to Complex A and the Orphan stream, and line-of-sight velocities for the latter. The method presented uses our current knowledge of the projected positions of the streams, as well as line-of-sight velocities for Complex A, and we show that a solution exists in which the two streams share the same orbit. If Complex A and the Orphan stream are on this orbit, our calculations suggest the Orphan stream to be at an average distance of 9 kpc, with heliocentric radial velocities of approximately $-95 \text{ km s}^{-1}$. Complex A would be ahead of the Orphan stream in the same wrap of the orbit, with an average distance of 4 kpc, which is consistent with the distance constraints determined through interstellar absorption line techniques.

Key words: Galaxy: structure — Galaxy: halo — ISM: clouds, kinematics and dynamics — methods: analytical

1 INTRODUCTION
High velocity clouds (HVCs) have been enigmatic since they were first discovered by Muller et al. (1963). They are defined as neutral hydrogen clouds which have anomalous velocities compared to what would be expected through a simple model of differential Galactic rotation. Most HVCs do not harbour stars and due to their general location away from the Galactic disk, determination of distances to them through interstellar absorption line techniques (e.g. Wakker & van Woerden 1997) is challenging. The technique has, however, been applied successfully to a handful of HVCs and a general location away from the Galactic disk, determination of distances has, however, continued to make it difficult to constrain theories for their origin.

Complex A is a system of high-velocity neutral hydrogen clouds and resides in the northern Galactic hemisphere. It has a distance bracket of $\sim 4.0 - 10$ kpc, determined through the detection and non-detection of interstellar absorption lines at the velocities of the clouds (van Woerden et al. 1999, Wakker et al. 1996).

The Orphan stream is a stellar stream discovered in the Sloan Digital Sky Survey (SDSS, York et al. 2000) Data Release 5 by Belokurov et al. (2005), and is located between Galactic coordinates $l \sim 200^\circ - 255^\circ$ and $b \sim 52^\circ - 48^\circ$. If the line of Complex A is traced towards the stellar stream, the two streams appear to be tantalisingly close to overlapping.

Fellhauer et al. (2007) investigated the possibility of the dwarf galaxy Ursa Major II (UMa II) being the progenitor of the Orphan stream. Their simulations of the orbit of the disrupting satellite are able to reproduce the observational data to within the errors. In their model, the Orphan stream is trailing behind UMa II with Complex A being ahead of the dwarf galaxy by a further wrap of the orbit.

As more stellar and gaseous streams continue to be found in the Galaxy, it becomes increasingly interesting to investigate whether associations between such streams can be found. In this paper, we consider the possibility that Complex A and the Orphan stream are related, but without including UMa II in our analysis.

In order to model the orbit of Complex A, we must have some realistic initial conditions. We assume Complex A to be a stream, in the sense that it is moving along itself, and determine most of these initial conditions from the observational data themselves. A mid-stream point is chosen as the "initial condition" (IC) point, for which we need the sky-projected position, a heliocentric distance $d$ and the full velocity vector in order for it to provide the initial conditions of the orbit for Complex A. The line-of-sight unit vector $\hat{z}$ can be determined since the Galactic longitudes and latitudes $(l, b)$ are known. Here and hereafter hats denote unit vectors. The distance $d$ to the IC point is treated as a free parameter, with the aim of obtaining a mutual orbit for Complex A and the Orphan

* e-mail: shoko@ast.cam.ac.uk
stream. The line-of-sight velocities after correction to the Galactic Standard of Rest, \( v_s = v_1 \), for Complex A are known (e.g. Hulsbosch & Wakker 1988, Hulsbosch 1986). In order to obtain the full space velocity for the IC point, we must first determine its velocity along the apparent stream (i.e. transverse to the line-of-sight vector) as well. We denote this component of velocity in the plane of the sky as \( v_s \), and the angle along the stream, measured from one end of the stream, as \( \chi \). The unit vector along the apparent direction of motion of the stream is given by \( \hat{s} = \frac{d\hat{l}}{d\chi} \) and \( d\chi/dt = \mathbf{v} \cdot \hat{s}/d = v_s/d \) from the usual equation for the transverse velocity. Now \( \mathbf{v} = d\chi/dt = \nabla \psi \) divided by \( d\chi/dt \). We then have the rate of change of line-of-sight velocity along the stream:

\[
\frac{dv_s}{d\chi} = \mathbf{v} \frac{d\hat{l}}{d\chi} + \frac{dv}{d\chi} \hat{l} = v_s + (\hat{l} \cdot \nabla \psi) \frac{d}{v_s},
\]

where \( \psi \) is the Galactic potential. Let \( K(\hat{l}) = d\psi/d\chi \); we then have the following solutions to the quadratic equation for \( v_s \):

\[
v_s = \frac{1}{2} \left( K(\hat{l}) \pm \sqrt{K(\hat{l})^2 - 4(\hat{l} \cdot \nabla \psi) \frac{d}{v_s}} \right).
\]

There are two possible solutions for \( v_s \) and the two must be distinguished through comparing the model orbit with the observational data. For the Galactic potential, we use a three-component Galactic model described by Paczynski (1990), which uses the Miyamoto-Nagai model for the disk and spheroid (Miyamoto & Nagai 1975) and a near-logarithmic potential for the halo. In equation 2, both \( \nabla \psi \) and \( d \) naturally depend on the assumed distance to the IC point. We therefore treat \( d \) as a free parameter and compute both forward and backward stretches of the orbit for different values of \( d \). For the distances involved, our solutions are insensitive to the precise form of the potential adopted, and we find, for example, that altering Paczynski’s disk scale length \( a_2 \) by \( \pm 35\% \) has a negligible effect on the results obtained.

At any given position along Complex A, we can determine all components of the velocity vector using one of the solutions for \( v_s \) and the observationally determined value of \( v_1 \). The two solutions provide orbits in opposite senses. Both are physically valid but we find that one can be ruled out on comparison of the computed orbit with the observational data.

In order to calculate the run of radial velocity along the stream, it is necessary to have a smoothed stream. Given the morphology of Complex A, we use the longitude and latitude combined, \((l+b)\), to provide us with a single variable as a measure of position along the stream. Plotting \( v_1 \) and \( l \) as a function of \((l+b)\) using data from van Woerden & Wakker (2004) and Davies (1974) and taking a line of best fit through each provides us with a means of extracting a smoothed stream. The run of radial velocity along the smoothed stream is shown in Figure 1 where we have fitted a second order polynomial to the points. The origin (zero point) has been arbitrarily chosen to be the lower latitude end of the stream. The analytic fit allows us to determine \( dv_1/d\chi \) and hence the transverse velocity component along the smoothed stream.

\[1\] This term will be used when referring to data from the modelled orbits. To transform this to heliocentric radial velocities, we subtract the component of the Sun’s velocity \([9, 232, 7]\ km\ s^{-1}\) along the line of sight to the position on the stream. The distance from the Sun to the Galactic centre is taken to be 8.5 kpc.

\[2\] Transverse to the line of sight.

![Figure 1. Run of line-of-sight velocity along Complex A, shown as a function of angle along the stream. \( \chi = 0 \) corresponds to the low-latitude end of the stream. The smoothed points for Complex A (crosses) have been fitted by a second order polynomial (solid line) and fit the data to \( \pm 7\ km\ s^{-1} \).](image)

Complex A fans out at higher latitudes and it is not possible to constrain the orbit through points of this stream alone. Our working hypothesis is that the Orphan stream and Complex A share the same orbit. By computing possible orbits for Complex A at different distances, we can determine whether it is possible for the stellar and gaseous streams to share the same orbit. If an orbit lies along both streams, then that will constrain the distance to Complex A, and hence the distance to the Orphan stream under this scenario. We can calculate the heliocentric radial velocities that the Orphan stream stars would be expected to have, and these may then act as ‘predictions’ to test our model, once stellar radial velocity measurements become available.

3 Results

The two solutions for the tangential velocity \( v_1 \) in equation 2 provide us with two possible orbits in the opposite sense. By comparing the observational dependence of \( v_1 \) on Galactic coordinates and what the model predicts, we find that the orbit must be in the same sense as that of Galactic rotation in order for our model to match the data for Complex A along its full length.

We computed orbits with different IC points, varying the distance \( d \) over a range of \( 1 - 40\ kpc \). Our best fit results are shown in Figure 2 where the initial conditions at the position \((l,b) = (146,33)^\circ\) are given by \( v_1 = -56\ km\ s^{-1}, d = 4\ kpc \) and \( dv_1/d\chi = -3.76\ km\ s^{-1}/\text{deg} \). The solid curve shows the forward-integrated orbit from the IC point and the backward integration is shown by the dotted curve. The value of \( v_1 \) at this point is \(-266\ km\ s^{-1}\), where the minus sign indicates that the direction which we took to be increasing \( \chi \) is opposite the actual direction of motion of the stream. The orbital time covered in Figure 2 lasts in total for 470 Myr. The position of Complex...
Figure 2. Top: best fit orbit for Complex A (solid and dotted lines), overlaid with observationally determined positions for Complex A (dots) and the Orphan stream (open triangles). The solid line denotes the forward orbit from the initial condition point and the dotted line the backward orbit. Initial conditions are \((l, b) = (146, 39)^\circ\), \(d = 4\) kpc, \(v_x = -56\) km s\(^{-1}\) and \(v_z = -266\) km s\(^{-1}\). Middle: heliocentric distances for the best fit orbit. Bottom: line-of-sight velocities for the same orbit, overlaid with observational data for Complex A (dots). The dot-dash line shows the range covered by the Orphan stream.

A [Hulsbosch & Wakker 1988] is denoted by dots and the Orphan stream illustrated by open triangles. The Orphan stream is a straight line going through \((RA, dec) = (162, 0)^\circ\) at an angle of \((90 - 21.0375)^\circ\) (Belokurov 2007, priv. comm.) and the positions denoted in Figure 2 were determined for 18 points between RA of 145° and 162°.

4 SUMMARY AND CONCLUSIONS

In this paper we have shown that by using the observational data of one stream, it may be possible to constrain distances to more than that stream. The calculation uses the observational radial velocity and positional data of the first stream together with the positional data for the second. Under an assumed Galactic potential, only the distance to the first stream is treated as a free parameter. Although it is not possible to determine the distance to Complex A alone using this method, the inclusion of a possible associated stream – the Orphan stream – into the procedure introduces the means to calculate distances to both streams and to predict radial velocities for the second stream, under the hypothesis that they are related through the same orbit.

Our results depend on the cores of the clouds of Complex A moving ballistically. The referee asked us to consider the possible effects of ram pressure in altering the orbit of the gaseous stream, an effect that would not be an issue for the stellar stream. This would be important in any crossing of the Galactic disk. We estimate that the clouds could travel for 5 kpc through a stationary medium of particle density \(\sim 10^{-3}\) cm\(^{-3}\) with a velocity change of \(\sim 20\%\) if they were to sweep up all of the gas in its way. The effect would be much smaller if the halo gas and the HVCs are rotating in the same direction or if we have overestimated the halo gas density. The effect of ram pressure is maximised in the above calculation but it should be noted that this result is only an order-of-magnitude estimate.

Our best fit results, assuming that Complex A and the Orphan stream lie on the same orbit in a Galactic potential defined in Section 2, predict them to be at average distances of 4 kpc and 9 kpc respectively. In this scenario, the two streams would be in the same wrap of the orbit, with the direction of motion coinciding with the direction of Galactic rotation and with Complex A ahead of the Orphan stream. The average heliocentric radial velocity of the Orphan stream would be approximately \(-95\) km s\(^{-1}\) with the velocity along the stream ranging from \(-155\) km s\(^{-1}\) on the side of Complex A to \(-30\) km s\(^{-1}\) at the other end. [Fellhauer et al. 2007] show in their Table 1 a summary of the distances and heliocentric velocities deduced by [Belokurov et al. 2007]. We find that our distance predictions increase in the opposite direction to theirs and that the values do not agree to within their errors. Two of their fields currently have velocity estimates of \(-35\) km s\(^{-1}\) and 105 km s\(^{-1}\), but these are very uncertain.

Vidrih et al. (2007, in prep.) have recently obtained radial velocity data for the Orphan stream stars in regions that correspond to fields 2 and 3 in Figure 1 of [Belokurov et al. 2007], and should be able to determine heliocentric radial velocities for stars in the region between \((l, b) = (215, 54)^\circ\) and \((242, 51)^\circ\). As an example of a location least contaminated with stars of the Sagittarius stream, we predict the heliocentric radial velocity at \((l, b) = (230, 53)^\circ\) to be \(-80 \pm 3\) km s\(^{-1}\). The indication of the error has been determined from an uncertainty measure in the initial condition distance of \(\pm 2\) kpc. These predictions will be tested when Vidrih et al. have reduced their data.

Many gaseous and stellar streams are known and continue to be found in the Galactic halo. If some of these seemingly disconnected streams are in fact associated with each other, then it would be interesting to have a method which attempts to find those associations.

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