Group Radio Astronomy (115 points)

Please read the general instructions in the separate envelope before you start this problem.

Measuring the Perseus arm using 21 cm HI line data

Context

Our goal here is to kinematically estimate the distance of (part of) the Perseus Arm of the Milky Way (Figure 1), from the center of the Milky Way, based on the line-of-sight velocity of neutral hydrogen gas via its 21 cm emission line.

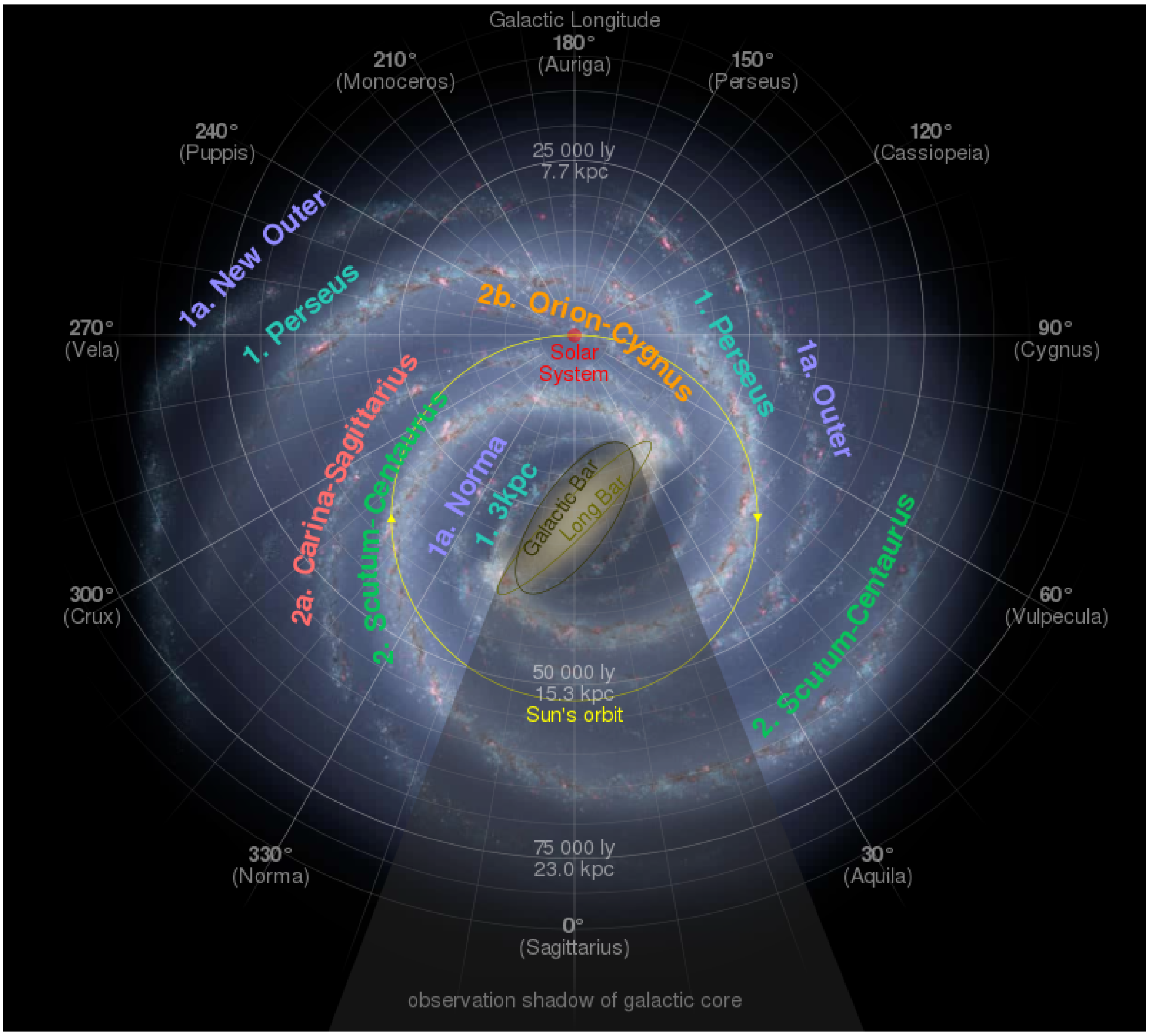

Figure 1: Distance-galactic longitude map of the Milky Way arms https://en.wikipedia.org/wiki/Perseus_Arm#/media/File:Milky_Way_Arms_ssc2008-10.svg

For this problem we will use a subset of the Canadian Galactic Plane Survey (CGPS, Figure 2), in which individual radio telescope pointings can each yield the 21 cm line spectrum emitted by all the galactic neutral hydrogen along the line of sight of the radio telescope.

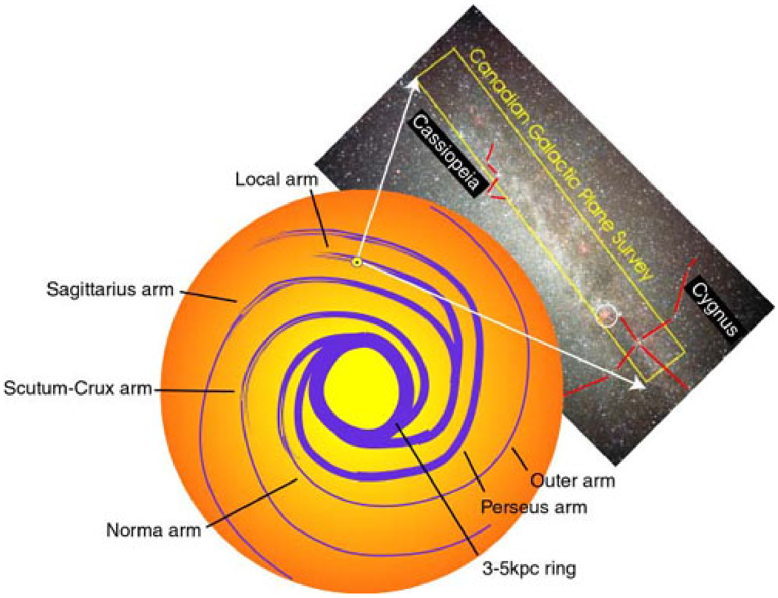

Figure 2: Canadian galactic plane survey http://www.ras.ucalgary.ca/CGPS

By translating the Doppler wavelength shift of the 21 cm emission to a line-of-sight velocity, it is then possible to identify individual emission components that correspond to distinct galactic arms. This identification allows for a reconstruction of the shape of each arm with respect to the Galactic Center.

In the spectrum corresponding to a radio telescope pointing, the Perseus arm can be readily identified because it is often the brightest feature along each line of sight.

The frame of reference of the radio telescope observations can be taken to be the Sun, located at a distance R_0 from the Galactic Center (GC). The telescope has a pointing along a Line of Sight (LOS) defined by a galactic longitude l and a fixed galactic latitude $b = 0$. Along this LOS, the telescope picks up the emission of a parcel of neutral H gas from the Perseus arm that is located at a distance r from the Sun. This same parcel of gas is located at a distance R from the Galactic Center. Let us assume that both the Sun and the gas parcel are in exact circular orbits around the GC. Additionally, it can be assumed that both the Sun and the gas parcel are in the region where the rotation curve of the Milky Way is flat. The measured (Doppler) velocity is denoted as $\mathrm{v}_{\mathrm{LOS}}$, which equals to the velocity of the gas parcel along the line of sight.

Data set

For this problem we attach a .csv file (21cmsurvey_full.csv, Excel and other spreadsheet software-readable) which contain 21 cm HI line brightness temperature (T_b) data vs. line-of-sight velocity (V_{LOS}) for a range of galactic longitudes (for galactic latitude $= 0$).

Row **1**: Line-of-sight velocities v_{LOS} (173 values, units: kms^{-1}).

Column **1** (after row 1): Galactic Longitude l (1024 values, units: $^\circ$).

Rows **2-1025**: 21 cm HI Brightness Temperature T_b (units: K). Each row yields the spectrum for the pointing defined by l (row name - column 1). There are thus 1024 spectra. Each spectrum has 173 T_b measurements, one for each v_{LOS}.

	A	B	C	D	E	F	G
1	longitude	17.499242	16.674782	15.850322	15.025862	14.201402	13.376942
2	142.195	7.6806355	-3.6773872	10.236036	12.072731	2.6496887	-5.4096527
3	142.2	-2.3566856	-17.443382	10.948601	15.752264	-5.6430779	-4.0766678
4	142.205	-7.2586327	-16.816818	11.409309	14.382421	-8.1247673	-2.1908302
5	142.21	-4.8997993	-1.3861237	8.1782017	0.1741447	-6.5460701	2.8831139
6	142.215	1.4211311	17.361675	3.865963	-19.79607	-5.4956512	10.672174
7	142.22	10.801174	29.229548	6.5995045	-28.279266	-6.2942162	17.140533
8	142.225	15.174841	25.408731	12.852865	-18.843937	-8.4810486	11.249598
9	142.23	11.863876	11.36631	13.676001	-3.8985252	-8.6407623	-3.4193878
10	142.235	1.5808449	-5.765934	4.6522408	3.5158234	-6.70578	-18.493797
11	142.24	-3.855526	-13.573421	-5.8457909	0.7269974	-4.1995239	-23.408031
12	142.245	-1.1465569	-7.5473442	-7.0313492	-3.400959	-1.7116928	-18.352516
13	142.25	5.9913673	8.6634827	2.0968399	-1.6011238	4.3635292	-6.9637794
14	142.255	9.1303349	24.567169	13.166147	4.2713852	13.448717	4.9778061

Part 1 (50 points).

1.1	Make a spectral plot of v_{LOS} vs. T_b for an adequate number of different values (at least 20 plots) of galactic longitudes covering the full range of observations. Identify the peak line of sight velocity of the Perseus gas parcel at each of the plotted longitudes. Make sure to evenly sample the data set. **Note:** Use the plot of the first or the last longitude as a guide to identify correct peaks in the plots at the intermediate longitudes.	45.0pt

1.2	Why does the emission near $v_{LOS} = 0$ (which we associate with our local arm) have a lower brightness temperature than the emission from the Perseus arm?	5.0pt

Part 2 (20 points).

2.1	Derive an expression to calculate R from v_{LOS}, $v_{\odot}$, and l. You can assume: • That both the Solar System and and the Perseus arm gas parcel along the line of sight have a purely tangential velocity, with a negligible radial component. • A flat galactic rotation curve, i.e. $$\lvert \mathrm{v} \rvert = \lvert \mathrm{v}_{\odot} \rvert$$ where v is the velocity of the gas parcel.	20.0pt

Part 3 (20 points).

3.1	Using the v_{LOS} values you found earlier, make a plot of galactic longitude l vs. R (radius with respect to the Galactic Center, in kpc) for the Perseus arm. Find the average distance of the Perseus arm for the given longitude range. Also report the standard deviation in your result. Use the values: $$v_{\odot} \approx 225\ kms^{-1}$$ $$R_0 \approx 8\ \mathrm{kpc}$$	20.0pt

Part 4 (25 points).

4.1	The data also shows 21cm emission from the Norma arm of the Milky Way, which is its outer arm. This emission is most clearly seen around the galactic longitude of 145^o. Repeat the exercise for the Norma arm to find its distance from GC. Use at least 5 data points to determine the distance of the Norma arm from the Galactic Centre (at these galactic longitudes).	25.0pt