STUDY OF THE OUTER GALACTIC STRUCTURE FOR $288° \leqslant l \leqslant 310°$, $-7° \leqslant b \leqslant 2°$

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(Received 31 May, 1973)

Abstract. The structure of the outer part of the Galaxy is studied, based upon 21-cm line observations of H I in the region $288° \leqslant l \leqslant 310°$, $-7° \leqslant b \leqslant 2°$.

In this longitude range the galactic plane is strongly bend toward negative latitudes.

The principal outer structure is a spiral arm which has a pitch angle of 10° and is formed by several concentrations differing in shape and size. There exists also a secondary concentration which could be a split from the previous structure.

Possible hypotheses about the origin of the later feature are discussed.

1. Introduction

It is well known from 21-cm line observations of neutral hydrogen that the galactic plane bends toward negative latitudes near those of the Magellanic Clouds (Burke, 1957; Kerr, 1957). This bend is the counter part of a bend toward positive latitudes at longitudes around 100°. So far the southern bend was analysed only in Surveys which follow closely the galactic plane, like the Sydney and the Parkes sky surveys which go both only to $-2°$. Similarly one of us (Garzoli, 1970) had only material reaching down to $-3°$. Later on however the survey was extended to $-7°$ and published as an Atlas (Garzoli, 1972).

The present paper is thus devoted to a study of the features present in this extended survey, mainly at those longitudes where the bending is more pronounced. The structure is studied in detail for longitudes between 288° and 310°. For longitudes less than 288° there is an overlapping of velocities between the outer structure and other nearby structures.

Two well separated structures were found in the external part of the Galaxy: one is the principal outer structure and the other a secundary concentration of neutral hydrogen. The latter exhibits peculiar characteristics, which show a close similarity

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with other concentrations found in our Galaxy and in the Magellanic Clouds. These two structures seem to be connected. The results of the 21-cm line analysis were compared with observations in the continuum of H II regions and supernovae remnants.

2. The Principal Outer Structure

We study the principal outer structure (POS from now on) for longitudes $288° \leqslant l \leqslant 310°$ by means of a detailed analysis of the countour diagrams at constant latitudes and

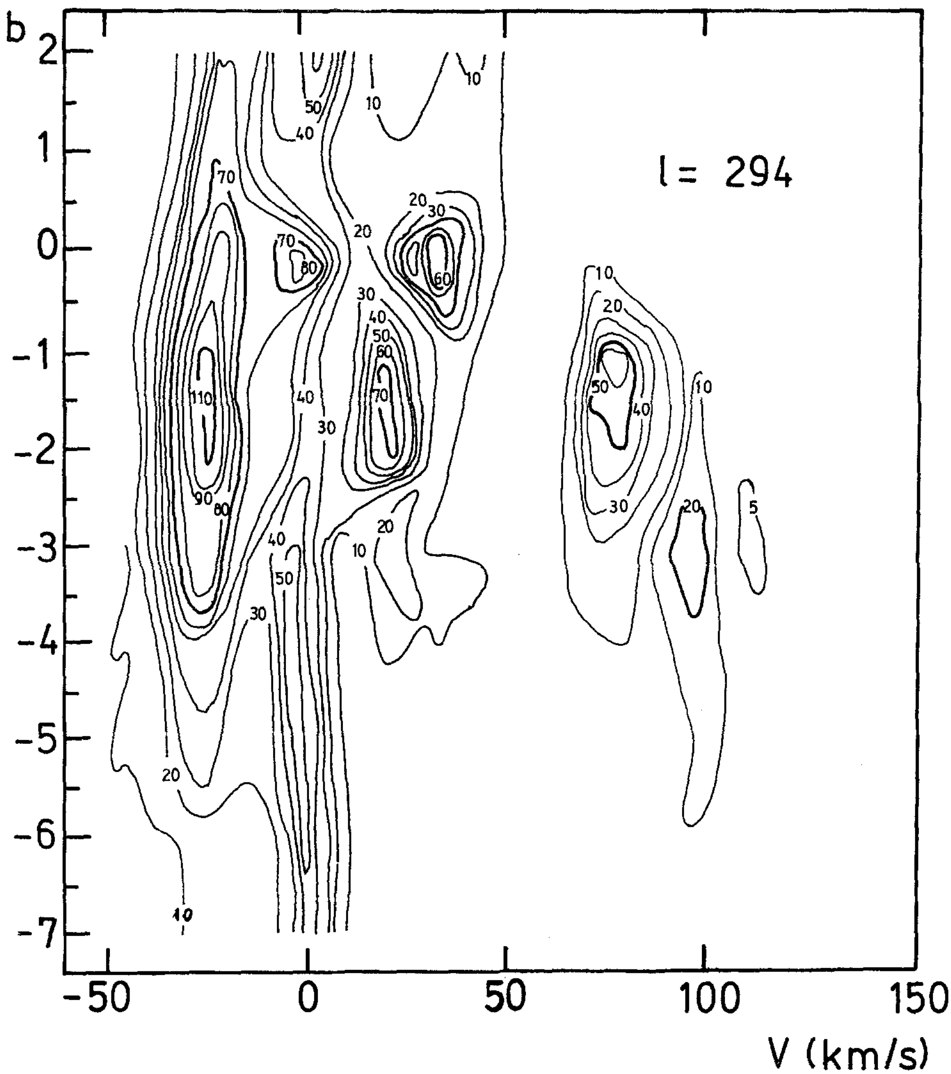


Fig. 1. Contour diagram of antenna temperature in degrees as function of radial velocity and latitude for longitude $l = 294°$. Centered at $b = 1°$ and $v = 78$ km s^{-1}, we can see a part of the principal outer structure.

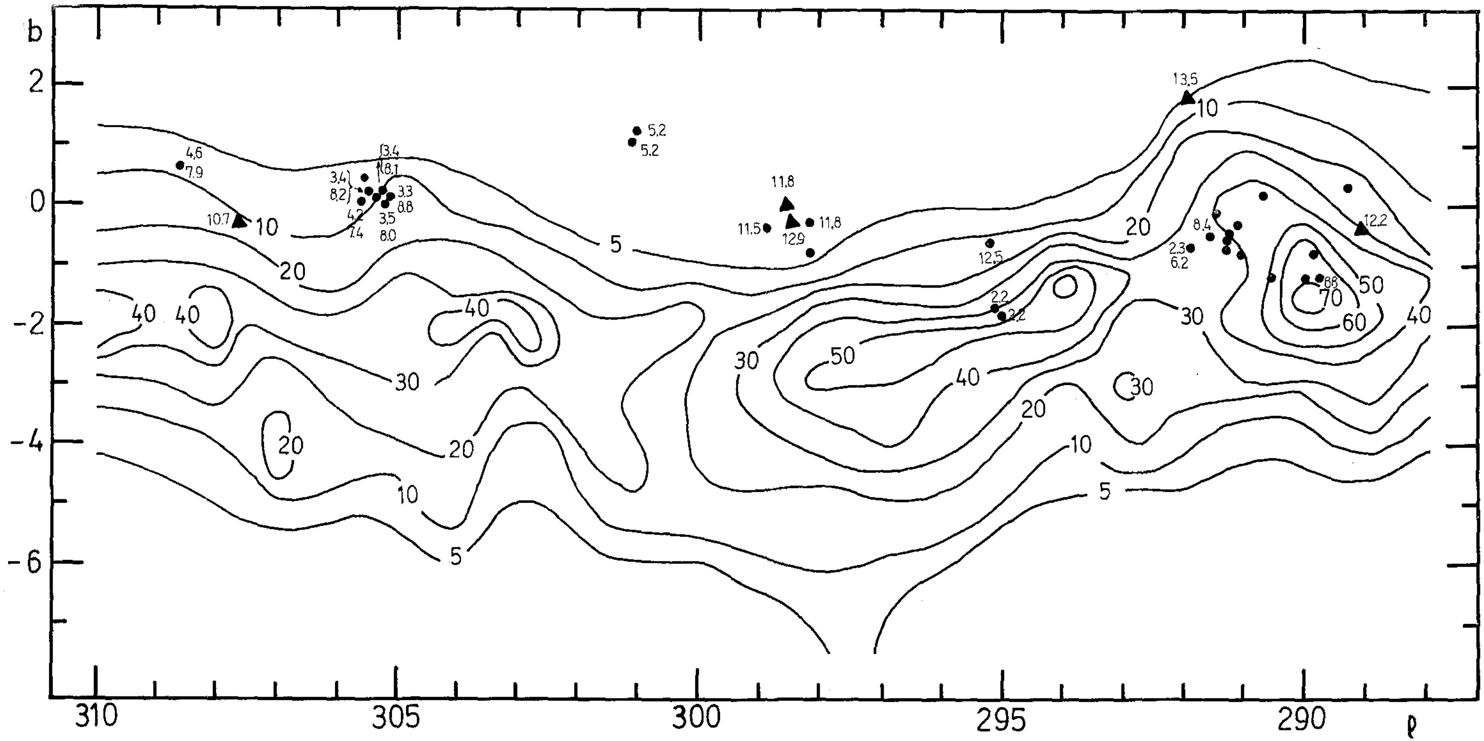


Fig. 2. Contour diagram of antenna temperature as a function of longitude and latitude for the velocity range corresponding to the outer principal structure. The continuum data available in the region are: ▲ Supernova, ● H II region. The number near the dots are the distances given for the H II regions, where available.

longitudes. The principal outer structure is clearly separated in velocity, within this range of longitudes, from the nearby structures. We show in Figure 1 some contour diagrams at longitude where this effect is clearest.

From the diagrams (b, v, l=cont) and (l, v, b=cont) we draw the contour diagrams (l, b) within the velocity range that corresponds to the POS (see Figure 2).

Looking at Figure 2 one can see that the bending of the POS toward negative latitudes is most pronounced for $l=297°$. It can also be seen that the structure is composed of concentrations with a geometrical center located between the latitudes $-1°$ and $-5°$. There are four main concentrations.

In Table I are given the parameters that define the POS. It was attempted to separate in the best possible way the different concentrations. The last column of the table provides also the heliocentric distances of the different concentrations, calculated on the basis of Schmidt's model of the Galaxy.

TABLE I

The principal outer structure parameters. Parameters corresponding to the outer principal structure (see text). The crosses (+) show the hydrogen located between concentrations.

l (o)	b (o)	T (K)	v (km s^{-1})	d (kpc)
288	−1 25	40	68	12.2
289	−1 75	50	71	12.7
290	−1.50	60	72	13.0
291	−1 70	40	73	13.3
291	0.25	40	56	11.7
+292	−1.00	30	90	14.8
293	−1.25	40	74	13.9
294	−1.20	60	78	14.4
295	−2.00	50	81	14.9
296	−2.20	50	80	15.0
297	−3.00	50	91	16.3
298	−3 00	50	92	16.7
+299	−2.60	30	81	15.9
+300	−3.80	20	80	16.2
+300	−1.90	20	85	16.6
+301	−4 30	20	84	16.8
+302	−2.60	20	84	16.8
+302	−2.80	20	81	16.8
303	−2.00	40	74	16.3
303	−2.99	30	90	17.9
304	−2.20	40	91	18.4
305	−2.10	30	91	18.9
+306	−2.50	20	79	17.9
+307	−2.10	30	88	19.2
308	−2.00	40	81	18.7
309	−1.75	30	90	20.0
310	−2.00	40	82	19.5

Concentration 1: Appears as having spherical symmetry and it is centred at $l=290°$ and $b=-1.5°$. Its peak temperature is 70 K and its velocity 72 km s^{-1}. From lower to higher longitudes there is a positive velocity gradient.

Concentration 2: Appears as a concentration spread out in longitude ($293.^{\circ}5 \leqslant l \leqslant \leqslant 298.^{\circ}5$) and latitude $-1° \leqslant b \leqslant -3°$. It shows a clear bending towards negative latitudes, in the direction of the bending of the POS. The peak temperature ($T=60$ K) is found at $l=294°$, $b=-1.5°$.

There is a positive velocity gradient going from 74 km s^{-1} at $l=293°$ to 92 km s^{-1} at $l=298°$.

Concentration 3: This is a small concentration and it is hard to define its boundaries in the (l, b) contour diagrams; it is however well defined in the (l, v) contour diagrams. The peak temperature ($T=40$ K) appears at $b=-2°$ for longitudes between 302.5° and 305°

Concentration 4: Our observations allow us to know only that this concentration starts at $l=307.^{\circ}5$, $b=-2°$ and extends towards higher longitudes. It shows two peaks that might or might not belong to the same concentration. Since our observations reach only to $l=310°$ we cannot decide this point.

The peak temperature is $T=40$ K and the velocity range is 80 km s^{-1} to 90 km s^{-1}.

One can see from Table I that for the concentrations 1, 2 and 3 there are positive velocity gradients for higher longitudes. Between concentrations the velocities do not follow this general tendency.

Figure 3 illustrates the run of the heliocentric distances computed with the Schmidt mass model, as a function of the longitude.

If the concentrations #1, #2 and #3 are used to define the direction of the POS, we are able to estimate the pitch angle as 10^0.

3. Two Other Concentrations near to the POS

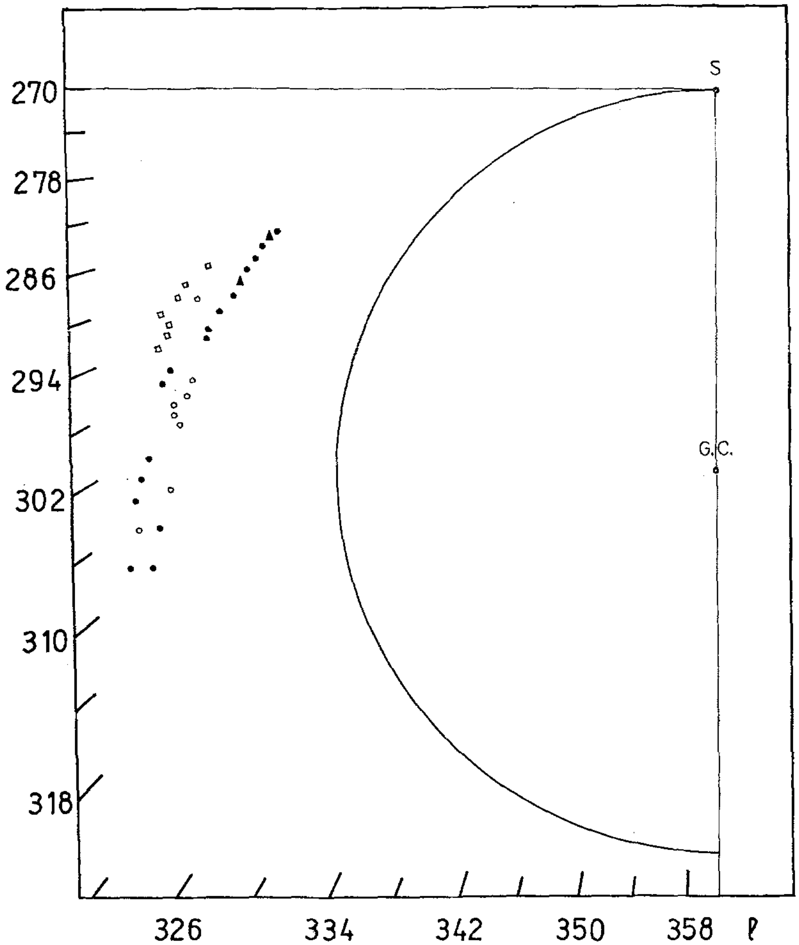
In the analysis of the (l, v) and (b, v) contour diagrams we found two other concentrations of a size and velocity such that we believe that they do not belong to the POS.

It is shown in Figure 1 that for $l=294°$ and velocities higher than 50 km s^{-1}, in addition to the POS at $v=78$ km s^{-1} there are two concentrations at $v=95$ km s^{-1}) and $v=115$ km s^{-1}. Of these two concentrations only the one of lower velocity (concentration A) could be studied in detail. The other one is of very low intensity and with our equipment the errors are too large to allow a detailed study.

In Figure 4 we show a plot of the (l, b) diagram for concentration A. This was obtained from the (l, v) and (b, v) contour diagrams at the velocities near $v=95$ km s^{-1}).

For longitudes between $290° \leqslant l \leqslant 295°$ this concentration is clearly separated from the POS, but for $l<290°$ it mixes with the POS. For $l \leqslant 288°$ and $l>296°$ it disappears completely. Looking at Figure 2 and 4 it is clear that the concentration A nucleus is located in a region where the POS has a lower density of gas. Also the nucleus of the concentration A is at lower latitudes than the POS concentrations.

Assuming small optical depth the surface density of neutral hydrogen was calcu-



ig. 3. Distances to the Sun as a function of the longitudes as given at Table I. The closed dots (●) correspond to the concentrations and the open circles (○) to the regions between concentrations for the outer principal structure. □ indicates structures that correspond to the *A* secondary concentration, ▲ indicates supernova remnants.

lated with the expression

$$N_H = 1.822 \times 10^{18} \int T_b \, dV .$$

In Figure 5 is plotted the surface density (in units of 10^{21} at cm^{-2}) together with the velocity diagram corresponding to the peak temperatures of the *A* structure.

From the N_{H} values and the heliocentric distances calculated from the Schmidt's mass model, it was estimated that the mass of the concentration is 2.3×10^{40} g, i.e. 1.2×10^7 solar masses. Taking into account the stability condition, one finds that the maximum rotational velocity for such a mass is 6 km s^{-1}. The fact that this value is smaller than the velocity difference between the borders and the center of the concen-

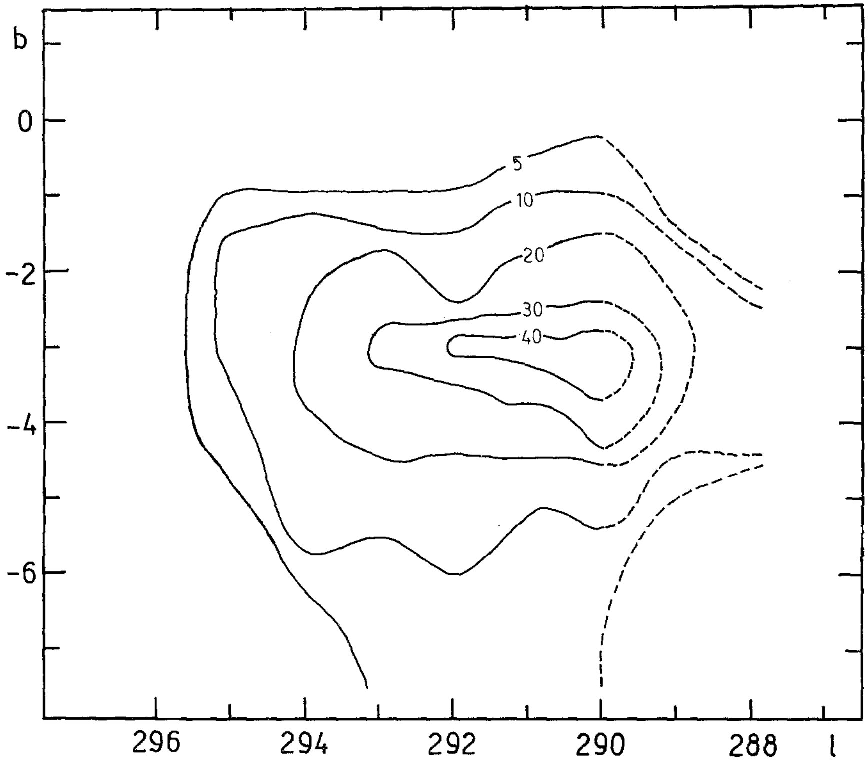


Fig. 4. (l, b) diagram of antenna temperature for the A concentration, as it appears from the (l, v) and (b, v) diagrams, for velocities near 95 km s^{-1}. Broken lines correspond to longitudes where this concentration starts to mix in velocities with the outer principal structure.

tration A (Figure 5) with the fact that the isovelocity lines show a maximum, implies that these velocity lines represent essentially a translation motion of the A structure and not a rotational motion. On the other hand it can be seen also that the velocity gradient agrees with the surface density gradient.

In Table II we give the parameters of the A concentration whereas in Figure 3 its spatial distribution is shown according to the Schmidt's mass model.

4. Comparison with Supernova Remnants and H II Regions

Considering the characteristics of concentration A that is, its location in a region where there is a lower density of gas in the POS and its translational motion, it appears possible that it could be a segregation from the POS. In order to examine this possibility we have compared our observations with the observations of the continuum. In Figure 2 the objects detected by the radio continuum observations are shown together with the POS.

The data for the H II regions were taken from Shaver and Goss (1970), Georgelin and Georgelin (1970a, and b), Wilson *et al.* (1970), MacGee and Gardnet (1968) and

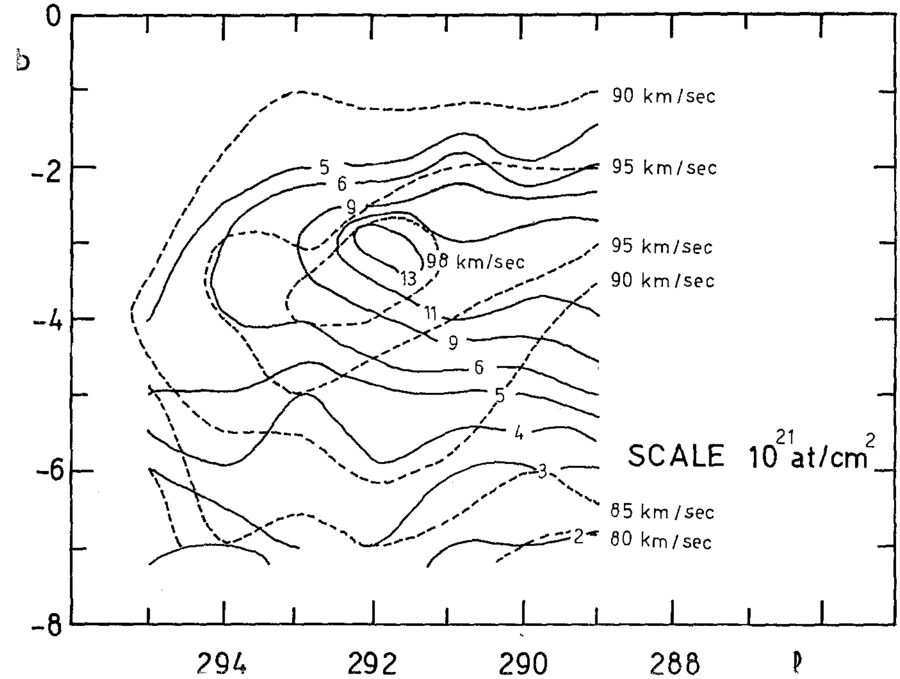


Fig. 5. (l, b) diagram of surface density in units of 10^{21} at. cm^{-2} (full lines) superposed on the velocity diagrams (broken lines) corresponding to the peak temperature for the A concentration.

TABLE II

The A concentration parameters. Parameters corresponding to the A concentration and estimated distances based upon Schmidt's mass model.

l (o)	b (o)	T (K)	v (km s^{-1})	d (kpc)
289	−3.0	?	91	14.2
290	−4.0	35	94	14.9
291	−3.0	33	96	15.2
292	−3.0	46	99	15.9
293	−3.0	29	94	15.7
294	−3.0	29	95	15.9
295	−4.0	17	93	16.2

Goss and Radhakrishnan (1969). In the Figure we show also the distances in those cases in which they have been calculated.

The data of the supernova remnants were taken from Shaver and Goss (1970) and Ilovaisky and Lequeux (1972).

4.1. Comparison with the Supernova Remnants

We show in Figure 2 the supernova remnants. The ones that are of most interest are those located at (1) $l=292\overset{\circ}{.}0$, $b=1\overset{\circ}{.}8$ at a distance of 13.5 kpc and (2) $l=289\overset{\circ}{.}1$, $b=-0\overset{\circ}{.}4$ at a distance of 12.2 kpc.

We show also in Figure 3 these two supernova remnants. One can see there that they are located at the same distance from the Sun than the POS gas, and they are at the same longitude as those of the concentration A. In particular the supernova remnant at $l=289\overset{\circ}{.}1$, $b=-0\overset{\circ}{.}4$ corresponds to the region where the concentration A and the POS mixe in velocity. This fact suggests its possible spatial connection.

The other supernova remnants is located at $l=292\overset{\circ}{.}0$ and $b=1\overset{\circ}{.}8$. This is a longitude region of the Southern Galactic Hemisphere where on one hand there is a lower density of gas in the POS and on the other the nucleus of the concentration A is located. This fact suggest the possibility that the structure A is a separation of the POS produced by a supernova. If this is so, the energy of the A concentration will be at most of the order of 10^{52} erg, corresponding to the kinetic energy of the ejected envelope of a type-II supernova (Shklovski, 1960). If one calculates the A concentration energy using a mass equal to 1.2×10^7 solar masses and a difference of velocity with respect to the POS of 30 km s^{-1}, one will get a energy of 10^{53} erg. This is an order of magnitude larger than what an explosion of a type-II supernova could give.

Hindmann (1967) in his studies of the Small Magellanic Cloud, finds a possible evidence of the existence of supernovae having energies of this order. He found three shell-like neutral hydrogen structures in the Cloud. They are about 10^7 solar masses, moving with expansion velocities of the order of 30 km s^{-1}. The average kinetic energy of these shells is about 10^{53} erg.

Rickard (1968) studied the peculiar motions of the Cas-Per arm. He found an expanding ring of about 10^7 solar masses with velocities of the order of 20 and 30 km s^{-1}.

The origin of this type of concentrations with energies higher than those explainable by supernovae has not been yet explained.

Shklovsky (1960) suggested the possibility of the existence of super-super-novae which might produce remnants an order of magnitude larger than those of the ordinary supernovae.

An alternative idea to the super-super-nova is the one proposed by Blaauw (1962). He suggested the possibility of several hundred normal supernovae exploding within a relative small volume over a short time span.

Another possible mechanism could be that a few very large supernovae, about ten, each ejecting 60 solar masses with kinetic energies of about 10^{52} erg. This mechanism has been proposed by Westerlund and Mattewson (1966) in the study of three supernova remnants in the Large Magellanic Cloud.

Independent of the particular mechanism that may originate the splitting of the concentration A from the POS, is the fact that the parameters that define it ($M=1.2\ 10^7$ solar masses, a relative velocity to the POS equal to 30 km s^{-1} and a kinetic energy of 10^{53} erg) are in agreement with the results of Hindman for the Small Magallanic Cloud and the ones of Rickard for the Cas-Per arm.

4.2. Comparison with the H II Regions

The distribution of the H II regions at longitudes between $l=288°$ and $l=300°$ show a tendency to lie below the galactic plane. For $l \geqslant 300°$ the tendency is to lie on or above the galactic plane (see Figure 2). It is also to be noted that the distance to the Sun is smaller than the one corresponding to the neutral hydrogen of the outer principal structure. This indicates that at these longitudes, there is a difference in the bending of the galactic plane for different distances to the Sun.

At longitudes between $l=280°$ and $l=292°$, there is a very large concentration of H II regions. This could explain the relative lack of hydrogen in the principal structure due to an absorption process.

5. Conclusions

The analysis of the POS based on surveys reaching down to $b=-7°$ confirm previous results of a maximum bending at $l=297°$, which at a distance of 16.3 kcp produce a maximum deviation of 850 pc.

This structure could be considered part of an outer 'spiral arm'. It is composed of concentrations of different shapes and sizes and has a pitch angle of 10°.

From $l=288°$ to $l=295°$ there exists a segregation from the POS. The nucleus of this secondary concentration is located in a region of relative lack of gas in the POS.

The velocity field in this concentration shows a translational gradient. This velocity gradient agrees approximately with the density gradient.

Due to the large mass and the difference of velocity between this concentration and the POS, it is not possible to think of this separation as originated by processes related to an explosion of a normal supernova located at the same heliocentric distance as the POS. The kinetic energy needed suggests as a possible mechanism one of the following alternatives:

(a) an explosion of a super-super-nova, (b) a few hundred explosions of supernovae within a relative small volume and (c) the explosion of a few supernovae, about 10, with energies of the order of 10^{52} erg.

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