AN ANOMALOUS VELOCITY NEUTRAL HYDROGEN STRUCTURE NEAR THE GALACTIC CENTER

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(Received 11 March, 1975)

Abstract. An extensive concentration of neutral hydrogen has been observed in the fourth galactic quadrant, with a mean radial velocity of $+44$ km s^{-1} referred to the local standard of rest. At a distance of R kpc from the Sun this structure would contain 2.5×10^4 R^2 solar masses of neutral hydrogen.

Five possible interpretations of this extensive concentration are considered: (1) part of the shell of a nearby explosive event; (2) a distant spiral arm of the Galaxy; (3) an extragalactic object; (4) material falling into our Galaxy; (5) gas expelled from the galactic center. Arguments are offered against the first three possibilities.

1. Introduction

In this paper a concentration of neutral hydrogen with anomalous radial velocity, located near the coordinates of the galactic center, is studied. The observed distribution and kinematics of this material will be compared to several models.

2. Observations

The observations here reported were made with the 30-m Argentine-Carnegie radiotelescope at the Instituto Argentino de Radioastronomía located in Parque Pereyra Iraola, Province of Buenos Aires, Argentina. The receiver uses a parametric amplifier front end and 56 channels of 10 kHz width spaced every 4 km s^{-1} at the frequency of

* Member of the Carrera del Investigador Cientifico del Consejo Nacional de Investigaciones Cientificas y Técnicas, Argentina.

** This Institution functions under an agreement between the Consejo Nacional de Investigaciones Cientificas y Técnicas, the Comision de Investigaciones Cientificas de la Provincia de Buenos Aires, the Universidad Nacional de la Plata and the Universidad Nacional de Buenos Aires, and with the support of the Carnegie Institution of Washington.

Astrophysics and Space Science **38** (1975) 381–394.

the 21 cm line. System noise temperature is near 250 K. A more complete description of the receiver has been given by Garzoli (1972).

In this study, observations were made at 180 points with an integration time of at least 12 minutes each over the velocity range -70 km s^{-1} to $+130$ km s^{-1}. Observed velocities were reduced to the Sun and to the local standard of rest by removal of the solar motion of 20 km s^{-1} toward $\alpha = 270°$, $\delta = 30°$ (1900.0).

3. Description of Results

Figure 1 offers as an example a profile taken at $l = 355°$, $b = -12°$. The 12 K peak at $+42$ km s^{-1} corresponds to the object under discussion in this paper.

Maps of antenna temperature at constant velocity, as well as diagrams of antenna temperature $T_A(l, V|b)$ and $T_A(b, V|l)$ have been constructed from the observations and Figures 2, 3, and 4 show examples of such diagrams for $b = -12°$, $b = -9°$, and $l = 355°$.

The intermediate velocity structure appears in general to be well separated from the

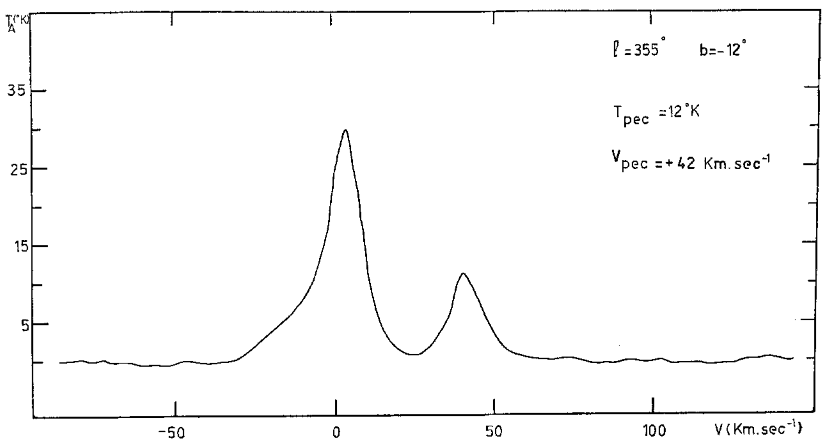

Fig. 1. Profile at $l = 355°$, $b = -12°$. The 12 K peak at $V = +42$ km s^{-1} corresponds to the feature under discussion.

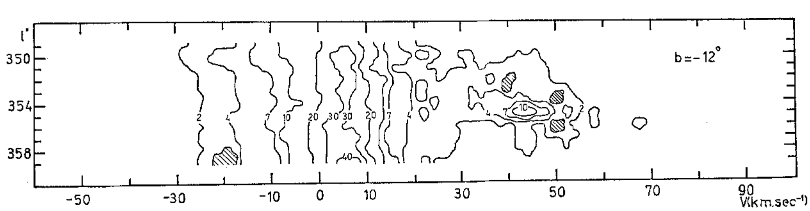

Fig. 2. Antenna temperature T_A (l, $V/b = -12°$).

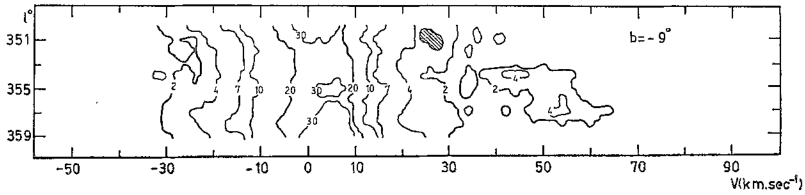

Fig. 3. Antenna temperature T_A (l, $V/b=-9°$).

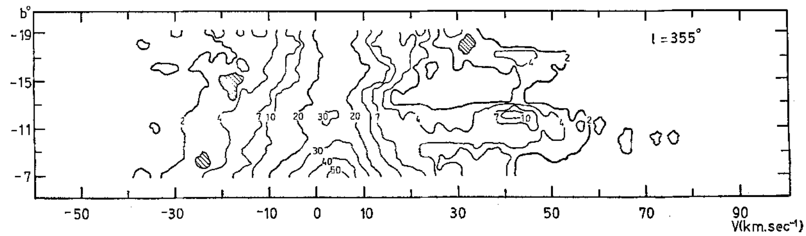

Fig. 4. Antenna temperature T_A (b, $V/l=355°$).

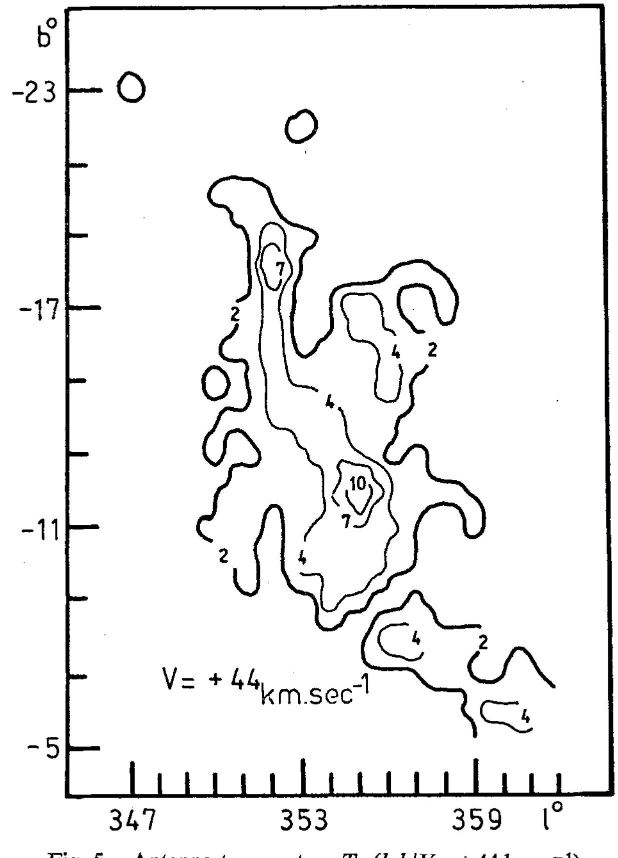

Fig. 5. Antenna temperature T_A (l, $b/V=+44$ km s^{-1}).

low velocity material. Nowhere in the region here discussed do we observe significant quantities of gas with radial velocity more negative than -30 km s^{-1}. The velocity structure of the local gas appears regular, without notable perturbations or 'holes' in the region where the intermediate velocity object is found. In Figure 3, the diagram for $b=-9°$, a velocity gradient, V increasing with increasing l, may be seen. The peak velocity of the local gas remains between $+4$ and $+8$ km s^{-1} throughout the region observed.

Figure 5 is a map of the gas with velocity within 1 km s^{-1} of $V=+44$ km s^{-1}. Here one may see the separation between the high latitude gas and that observed near the galactic plane.

The observations are summarized in Table I, which provides, for the intermediate velocity profile at each point, the galactic longitude and latitude, the surface density of H I, the velocity of the peak and the velocity half-width at half-maximum temperature. The surface density has been calculated assuming small optical depth from

$$N_{\mathrm{H}} = 1.822 \times 10^{18} \int T_b \, \mathrm{d}V \; (°\mathrm{Kelvin, km\ s^{-1}}), \tag{1}$$

where the integral has been taken over velocities greater than $+30$ km s^{-1}. For points closer to the galactic plane than $b=-7°$ any separate intermediate velocity features are lost in the broad wings that characterize profiles near the galactic center. These points in Table I and on the maps should not be interpreted as having necessarily any connection with the feature observed farther away from the plane. Furthermore, several of the well separated intermediate velocity features extend to velocities less than $+30$ km s^{-1}. This gas is not included in the surface density integrals. We estimate that this 'left out' gas constitutes less than 10% of the total mass.

With the values of N_{H}, the mass M of the object can be computed using the expression

$$\frac{M}{M_{\odot}} = 2.44 \times 10^{-18} R^2 \sum_i \Delta S_i N_{\mathrm{H}_i}, \tag{2}$$

where R (in kpc) is the distance to the Sun, ΔS_i (in square degrees) the area of a surface element on the sky, and N_{H_i} (in atoms cm^{-2}) its corresponding atom density. The summation extends over the whole observed region. The result is $M=2.5\times 10^4 \, R^2 \, M_{\odot}$.

The half-power half-widths were estimated by averaging the half-power half-widths on both sides of the secondary peak. Features which were either too weak, or too blended with the main peak, to permit good estimates of V_p or ΔV are not included in Table I.

Figure 6 presents a map of the integrated brightness temperature given in units of 10^{20} atoms cm^{-2}, with the assumption of low optical depth. An elongated structure comprising clumps of material embedded in a more diffuse background is evident. The solid arrow drawn through this cloud points in the direction of the galactic center.

TABLE I

Summary of the results for the anomalous velocity neutral hydrogen structure

l (°)	b (°)	N_H (10^{19} atoms cm^{-2})	V_P (km s^{-1})	ΔV (km s^{-1})
347	−23	5	+41	4
348	−17	2	+27	5
	−19	4	+26	4
	−22	3	+31	3
349	−17	3	+34	3
	−19	4	+33	4
	−22	4	+33	2
	−23	4	+31	
350	−10	5	+31	7
	−13	5	+40	7
	−14	4	+40	4
	−17	3	+32	3
	−18	9	+37	6
	−19	4	+33	3
	−20	5	+33	
	−22	7	+35	3
351	−10	12	+34	8
	−11	11	+46	8
	−12	7	+42	6
	−14	9	+38	10
	−15	4	+30	7
	−16	8	+38	7
	−17	7		
	−19	9	+33	
	−20	12	+33	5
352	−10	6	+35	7
	−11	5	+32	7
	−12	7	+35	8
	−13	8	+32	9
	−14	12	+35	10
	−15	14	+39	7
	−16	10	+38	
	−17	10	+45	5
	−18	15	+42	3
	−19	19	+39	5
	−20	8	+39	4
	−21	4	+35	3
353	−10	23	+38	8
	−11	23	+36	7
	−12	9	+35	
	−13	14	+32	10
	−14	25	+36	10
	−15	6		
	−19	6	+32	3
	−20	4	+37	4
354	−9	12	+46	9
	−10	24	+36	11
	−11	18	+40	8
	−12	14	+36	10

Table I (Continued)

l (°)	b (°)	N_H (10^{19} atoms cm^{-2})	V_P (km s^{-1})	ΔV (km s^{-1})
354	−13	27	+39	8
	−14	14	+39	10
	−15	7	+43	10
	−17	5	+40	
	−18	9	+34	4
	−19	6	+33	
355	−9	10	+51	9
	−10	25	+43	10
	−11	22	+47	9
	−12	28	+41	7
	−14	3	+44	6
	−15	4	+47	5
	−16	7	+44	9
	−17	13	+44	4
356	−8	7	+45	4
	−9	6	+55	
	−10	17	+56	10
	−11	28	+44	10
	−12	6		
	−13	5	+47	7
	−14	6	+40	7
	−15	11	+45	6
	−16	13	+46	9
	−17	6	+45	4
	−18	9	+40	
357	−8	16	+45	11
	−9	11	+55	7
	−10	10		
	−11	12		
	−12	5	+44	9
	−13	5	+49	
	−16	5	+45	
	−18	6	+42	5
358	−7	10		
	−8	15	+47	10
	−10	6	+30	8
	−12	5	+44	9
	−17	7		
	−18	10	+34	6
359	−7	14		
	−8	12	+46	10
360	−5	14		
	−6	17		
	−7	7		
361	−5	25		
	−6	19		
	−7	9		
362	−5	22		
	−6	19		
	−7	6		

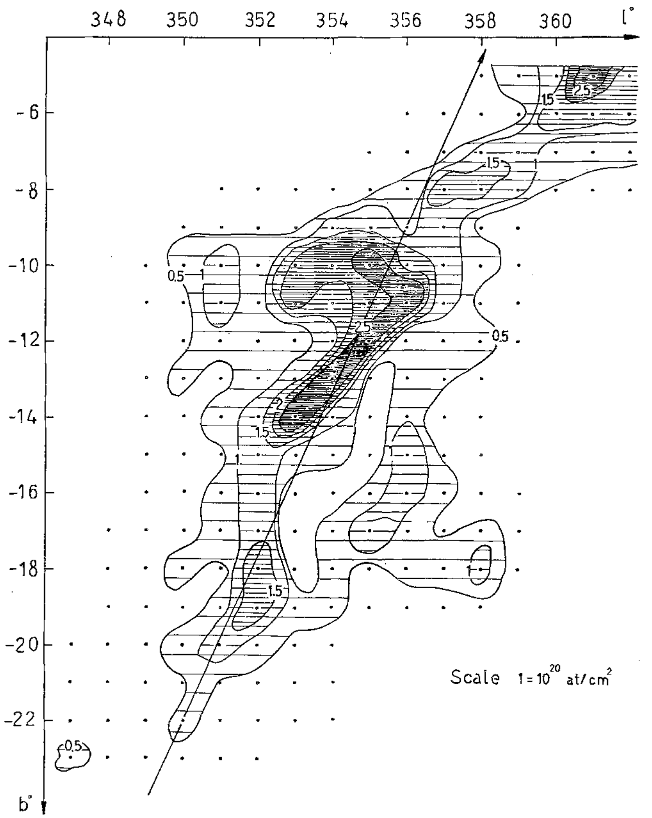

Fig. 6. Integrated brightness temperature for $V > +30\ \mathrm{km\ s^{-1}}$. The contour units are 10^{20} atoms $\mathrm{cm^{-2}}$. The arrow indicates the direction of the galactic center. Small circles represent the points observed.

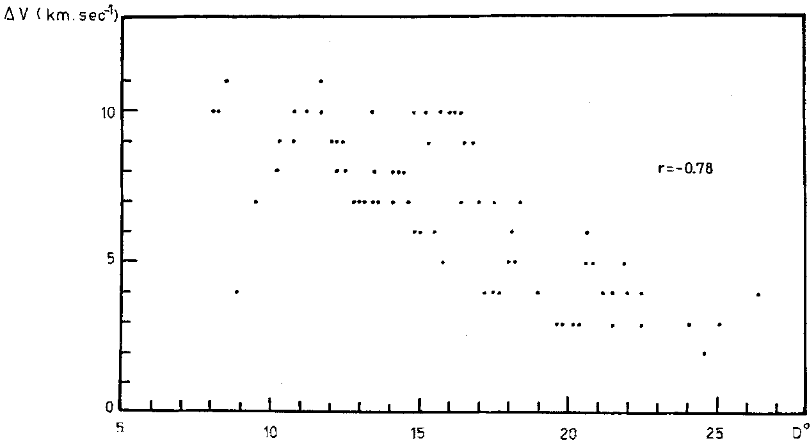

Fig. 7. Velocity half-width to half maximum in $\mathrm{km\ s^{-1}}$ against distance to the galactic center in degrees. The correlation coefficient is -0.78.

It may be easily seen that the gas is elongated in this direction. Each point observed in this region is indicated by a dot on the map.

In Figure 7, the velocity half-width of the profile for each point, against distance in degrees from the galactic center is plotted. A definite correlation may be noted, in the sense that the gas further away from the galactic center exhibits less velocity dispersion. The correlation coefficient for this is -0.78.

On the other hand, no correlation has been observed between surface density of gas and velocity half-width.

4. Comparison with Optical Data

Hill (1970, 1971) has published spectra and photometry for four early type stars in this region which exhibit interstellar Ca II. Table II reproduces his results. His velocities have been reduced to the local standard of rest using a solar motion of 20 km s^{-1}

TABLE II[a]

Stars with interstellar Ca II lines in the region of the anomalous velocity neutral hydrogen structure

Star	l	b	Spectrum	m_v	$V_{\mathrm{Ca\,II}}$ (km s^{-1})	V_r star (km s^{-1})	d (pc)
HD 170385	351°.10	−14°.99	B3V	7.90	−4	+1	759
HD 171141	349°.28	−16°.51	B1III	8.38	+14	+8	3388
HD 172094	353°.49	−15°.80	B2III	8.28	+20	+50	2089
HD 173994	348°.45	−19°.62	B2V	7.07	+10	−3	724

[a] The data are from Hill (1970, 1971).

toward $l=56°$, $b=23°$. The distance estimates were made using the absolute magnitudes that correspond to Keenan's (1963) spectral types and Johnson's (1963) intrinsic colors. In no case do we find coincidence between the Ca II velocities and the H I gas velocities. Hill considers that the star HD 172094 is probably a velocity variable, as is HD 173994.

5. Interpretation of the Results

The principal problem in the interpretation of these observations is the determination of the distance of this material.

A. AN OBJECT NEAR THE SUN

There are several facts which make it unlikely that it is an object very near the Sun. In the first place, the standard model of galactic rotation predicts negative radial velocities for material in the plane inside the solar circle at these longitudes, while the gas one observes has positive radial velocity.

Let us assume next that the material has acquired its anomalous velocity through some nearby explosive event, such as that of a supernova. If one takes a typical supernova outburst energy equal to 10^{51} erg, and uses a velocity of $+40$ km s^{-1} and a shell mass of $2.5 \times 10^4 R^2 M_\odot$ as representing this cloud, by equating the outburst energy to the kinetic energy of the cloud one finds that it can be at most only 1.6 kpc away. (Although the energy output of a supernova is somewhat uncertain, this is a conservative calculation, since all the energy will certainly not go into accelerating this cloud.) However, nothing resembling a supernova remnant appears in this region. On the southern extension of the Palomar sky survey, we see no emission nebulosity in this area and the nearest obvious obscuration is several degrees away. No radio feature in the continuum obviously associated with this feature has been noted.

Furthermore, if this material is gas near the Sun expelled from the plane by some explosive event, one might expect to observe also considerable perturbation or 'holes' in the local gas, and perhaps also much gas at velocities smaller than -30 km s^{-1}. Neither one of these effects are observed. The $T_A(l, V|b)$ and $T_A(b, V|l)$ isophotes of Figures 2, 3, and 4 demonstrate this quite clearly.

Finally, the interstellar Ca II lines appearing in absorption in this region show no correlation in velocity with the intermediate velocity H I gas. One turns then to some more distant models.

B. A DISTANT ARM OF THE GALAXY

This hypothesis is improbable for two reasons, one being the great extension of the structure in latitude, the other being the constancy of velocity with longitude. For a distant arm in the outer part of the Galaxy with regular rotational motion, we would expect to observe a velocity gradient.

C. AN EXTRAGALACTIC OBJECT

With respect to this hypothesis, one can distinguish two possibilities: (1) The object is a galaxy. Considerations of angular size put an upper limit to the distance, because the angular size of this feature is nearly 18°, and at a distance R, this corresponds to a linear dimension of

$$L = 2R \tan 9° = 0.3R.$$

This certainly puts the object within the local group of galaxies, since a distance of 100 kpc would imply a linear dimension of 30 kpc. One may note that in the Palomar Sky Atlas this region exhibits no peculiarities. Two globular clusters are visible on the print but no galaxies, due to obscuration by the central bulge of our Galaxy.

Whenever an object is observed over a large angular range, the projection of the motion of the local standard of rest due to galactic rotation will produce a gradient in the observed radial velocities. If one wants to study the intrinsic motion of an object that does not participate in the galactic rotation, this component must be removed. If the value of the galactic rotational velocity of the local standard of rest used

(250 km s^{-1} toward $l=90°$, $b=0°$), is in error by 50 km s^{-1}, the magnitude of the gradient in galactocentric velocities of the structure would change by about 20%.

Consider now if the galactocentric velocity gradient may be understood as due to rotation about the center of mass of the object. For this one calculates the circular velocity, V_c, at the edge of the cloud assuming all its mass to be concentrated at the center. A factor is introduced to allow for the possibility that only $1/f$ of the total mass is in the form of neutral hydrogen. Then

$$V_c = \left(\frac{GfM_H}{D}\right)^{1/2},$$

where G is the gravitational constant, M_H the mass of the structure in the form of hydrogen and D the distance from its center to the edge. If one takes 5° for the angular distance of the edge to the center, one has $D=R \tan 5°$ where R is the distance to the object. Using this relation, together with the distance dependent mass estimate, we obtain

$$V_c = 1.1(Rf)^{1/2} \text{ km s}^{-1},$$

with R in kpc. From Table I, we get $V_c=20$ km s^{-1} implying that the object may only rotate stably for $Rf>330$ kpc.

That is, angular size consideration implies a distance less than 100 kpc, while dynamical factors allow (for $f=1$) only distances greater than 330 kpc. One is led to conclude that the object is not a distant galaxy.

(2) A second possible interpretation of the cloud as extragalactic material is that it represents debris from the Small Magellanic Cloud, removed during a close passage to our Galaxy about 500 million years ago. Such possibilitie shave been studied by Toomre (1971), who suggested two zones in which such debris might be found. A survey of these zones in search of this material has been reported elsewhere (Mirabel and Turner, 1973).

The object here discussed lies roughly parallel to these zones, displaced from one of them by about 20°.

There are several arguments against this explanation; namely, (1) The radial velocity field is not coincident with that predicted by Toomre. (2) The gas lies well away ($\simeq 20°$) from the closest zone given by Toomre. This is, however, not a very strong argument, since many factors were neglected in Toomre's exploratory calculations. (3) The concentration of gas observed does not appear to continue to more negative latitudes, whereas the 'debris model' implies a more extensive distribution.

D. MATERIAL FALLING INTO OUR GALAXY

The direction of elongation (Figure 6), permits us to imagine that one is looking at material falling into the region near the galactic nucleus. Since the radial velocities observed after removal of the component due to galactic rotation of the L.S.R., are mostly positive, one would then locate the material between the Sun and the galactic center.

On the basis of this model, one can perhaps understand the observed increase of velocity half-width with decreasing distance from the galactic center (Figure 7). When infalling material approaches the plane, there will be an increasing number of collisions and progressive mixing with galactic gas. This would be expected to produce increased turbulence and, hence, broader profiles as the plane is approached.

If one assumes that the galactocentric velocity field is due to a translational motion of the structure as a whole, one can write

$$V = \mathbf{V} \cdot \mathbf{r},$$

where V is the radial velocity, $\mathbf{V}$ the velocity of the object, and $\mathbf{r}$ is a unit vector along the line of sight. Then for each observed point one can write:

$$V = V_x \cos b \cos l + V_y \cos b \sin l + V_z \sin b,$$

where V_x and V_y represent motion toward $l=0°$ and toward $l=90°$, $b=0°$ respectively, while V_z represents motion perpendicular to the galactic plane. Solving for V_x, V_y, and V_z by standard least squares techniques, we obtain:

$$V_x = +46 \pm 10 \text{ km s}^{-1},$$
$$V_y = +306 \pm 80 \text{ km s}^{-1},$$
$$V_z = -5 \pm 40 \text{ km s}^{-1},$$

with a rms dispersion about this model of 5 km s^{-1}. The uncertainties indicated above are those which double this dispersion. In Figure 8, the observed velocity field, after removal of the component due to galactic rotation of the L.S.R., is compared with that predicted by this model.

On the assumption that the material as a whole has a single space velocity, the motion is roughly parallel to the plane with a velocity of about +310 km s^{-1}, moving nearly parallel to the L.S.R. The small V_z component is not sufficiently well determined to permit us to infer motion toward or away from the plane.

E. GAS EXPELLED FROM THE GALACTIC CENTER

Observations of neutral hydrogen near the galactic center have revealed the existence of expansive motions (Rougoor and Oort, 1960; Rougoor, 1964; Van der Kruit, 1970).

The elongated shape of the object studied, and its orientation strongly suggest that one is here dealing with material ejected from the galactic nucleus.

One might then understand the decrease of velocity half-width with increasing distance from the nucleus as follows: Imagine the gas ejected some time ago with a velocity V, plus a smaller random component ΔV. At later times, the gas with ΔV in the same direction as V will be furthest from the center, and will exhibit small dispersion. Gas with ΔV perpendicular to V will be both closer to the source, more widely distributed, and have larger velocity dispersion. The low dispersion material due to ΔV opposite to V is, on this model, lost in the galactic gas near the plane.

Van der Kruit (1970) has found a number of structures outside the galactic plane

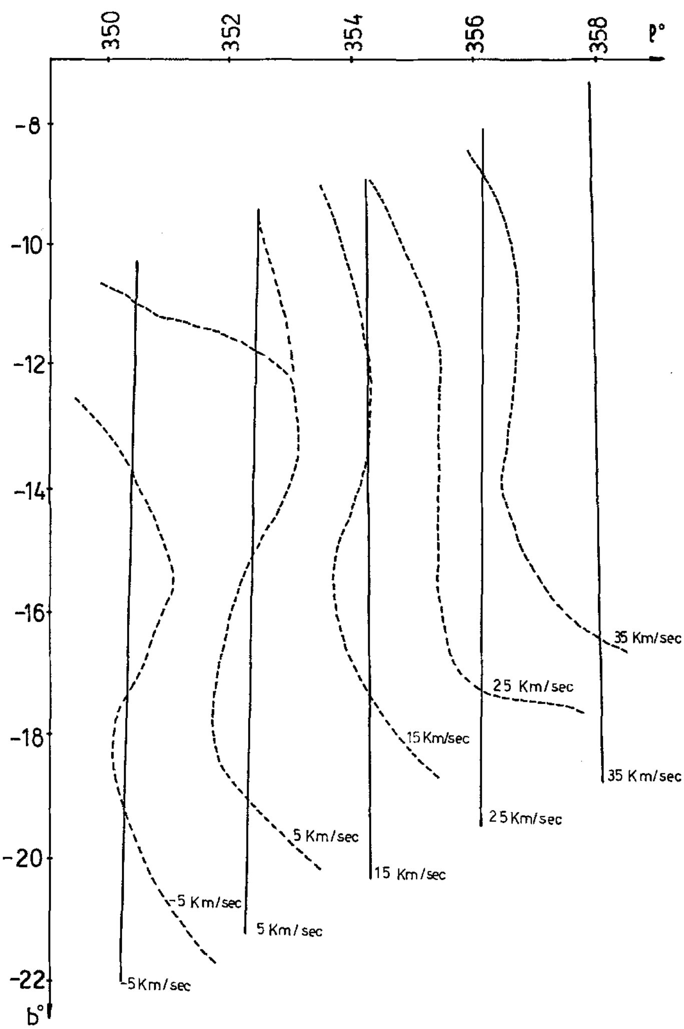

Fig. 8. Full lines indicate the model radial velocity field given by $V_x = +46\ \mathrm{km\ s^{-1}}$, $V_y = +306\ \mathrm{km\ s^{-1}}$, $V_z = -5\ \mathrm{km\ s^{-1}}$, dashed lines represent the observed velocity field, corrected for the effect of galactic rotation of the L.S.R.

with 'forbidden' velocities (i.e., 'forbidden' under the hypothesis of ordinary galactic rotation) which he believes to have been ejected from the galactic nucleus. In Figure 9 isophotes of integrated brightness for all the objects near the galactic center with anomalous radial velocity are shown. Structure 'A' is the one reported here, structure 'B' has been studied by Mirabel *et al.* (1975), structure 'C' has been studied by Mirabel and Franco (1975), and structures VII, X, XII and XIII by Van der Kruit (1970).

One may observe in Figure 9 that for the objects labeled B, C, VII, X, and XII, those with positive longitudes and negative velocities are below the plane, while those with negative longitudes and positive velocities are above it. Van der Kruit interprets

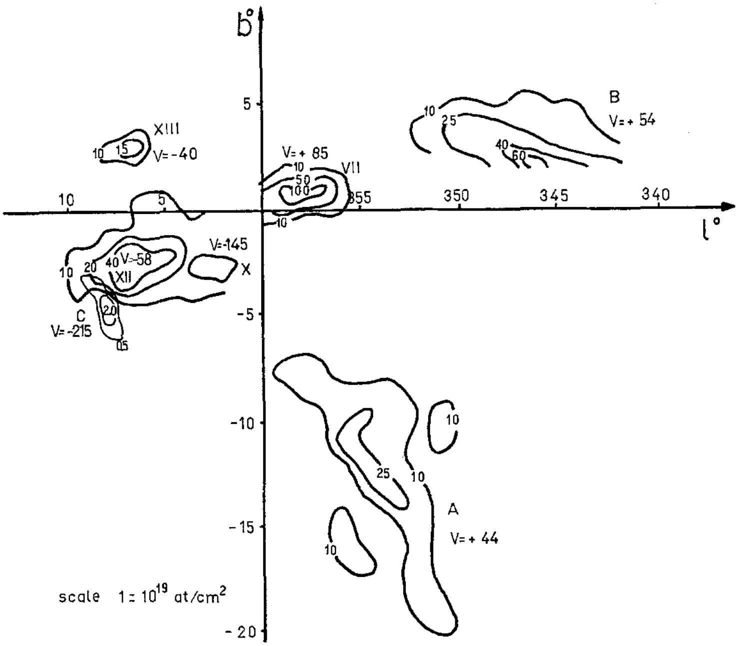

Fig. 9. Anomalous velocity structures near the galactic center. The contour units are 10^{19} atoms cm^{-2}. Velocities are with respect to the local standard of rest. The objects identified with roman numerals are taken from Van der Kruit (1970). Feature 'A' is discussed in this paper. Feature 'B' has been studied by Mirabel *et al.* (1975), feature 'C' by Mirabel and Franco (1975).

this as evidence for an expulsion of material in two opposite directions. If this is the case, structure A, together with the structure XIII, would suggest an ejection along a line roughly perpendicular to the first one.

If one interprets the observations in this way, one should place structure A beyond the galactic center while object XIII should lie between the Sun and the center of the Galaxy in order to relate the observed radial velocities with motion away from the nucleus. There is a small contradiction here, for the relative angular sizes of these objects would suggest that these relative distances be reversed.

It would be of interest to know if there is more material lying along the line defined by A and XIII. To investigate this in a preliminary way, the survey of Pöppel and Vieira (1975) was examined in the area $5° \leqslant b \leqslant 17°$, $0° \leqslant l \leqslant 12°$. (These observations were made on a 1° grid.) However, in this region, no gas was observed with $T_A > 5$ K and with velocity between -30 km s^{-1} and -80 km s^{-1}.

It was shown that the velocity field can not be understood as due to stable rotation about center of mass of the object. On the other hand, if one assumes the galactocentric velocity gradient to be due to simple translation, it is found that the motion is in general toward the galactic center and not away from it. The hypothesis that this gas has been expelled from the center is the only one congruent with the galactocentric velocity distribution if one imagines the structure to be undergoing considerable differential rotation about the galactic center as well as expanding away from it.

6. Conclusions

On the basis of various arguments, a number of tentative interpretations of the object were eliminated; namely, those attributing it to a nearby explosive event, to a distant arm of the Galaxy, to a galaxy in the local group and to S.M.C. debris.

There remain two hypotheses: (*a*) that one is observing material falling into our Galaxy from outside, or, (b) material just ejected from the galactic nucleus.

Under the hypothesis of infalling material we note that, under the assumption of uniform translatory motion, the galactocentric velocity field implies motion roughly parallel to the galactic plane and toward the center. No strong evidence is found for motion toward or away from the plane.

Under the hypothesis that this material is being expelled from the galactic center, one must assume that the material also shares in some way in the galactic rotation. One may only understand the galactocentric velocity field by a suitable combination of these two motions. If the material was expelled from the galactic nucleus by some explosive event, the direction of expulsion forms an angle of about 60° with the plane, and the energy of the explosion must have been higher than 5×10^{52} erg. This structure contradicts the general V, l, b symmetry found by Van der Kruit for the anomalous radial velocity neutral hydrogen structures near the galactic center. This fact suggests the possibility of ejection of matter from the galactic nucleus, also in the southern part of the fourth galactic quadrant.

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