

AN EXPANDING HIGH VELOCITY HI CLOUD PROBABLY EJECTED FROM THE GALACTIC NUCLEUS

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Abstract. An object located approximately at $l=8^\circ$, $b=-4^\circ$ with a mean radial velocity of -212.3 km s $^{-1}$ has been observed in the 21 cm neutral hydrogen line. The mean weighted velocity dispersion is 11.2 km s $^{-1}$ and the total mass is estimated to be $190 R^2$ (kpc) solar masses. We discuss possible interpretations of the origin and nature of this object. The most likely interpretation is that we observe an expanding object which has been ejected from the galactic nucleus.

1. Introduction

In the year 1967, in the course of a neutral hydrogen survey in the proximity of the galactic center, Shane (as quoted by Hulsbosch, 1968; Oort, 1968) noted a weak emission profile at galactic coordinates $l=8^\circ$, $b=-4^\circ$. The radial velocity of the object was -215 km s $^{-1}$ with respect to the LSR. This object has been reobserved by van der Kruit (1970), but has not been studied in detail until 1973. Its extension was unknown, and there was no information available about the velocity gradients in the object. The object has a very high radial velocity, of opposite sign than that expected in this part of the Galaxy according to a circular rotation model. Taking into account that objects close to the galactic center, and with anomalous radial velocities may constitute evidence for the activity of the galactic nucleus, we performed a detailed study of this object (Mirabel, 1974; Mirabel and Franco, 1974). Independently, and without knowledge of the authors, Saraber and Shane (1974) performed a similar study to which we will refer when appropriate.

2. Observations and Reductions

The profiles were observed with the 30-meter dish of the Instituto Argentino de Radioastronomía, at Parque Pereyra, Argentina, during the period going from December,

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1973, to June, 1974. The beamwidth of the antenna at 21 cm is 0.5° , the system temperature is 250 K. Two different banks of filters have been used. Firstly, we use a bank of 30 filters of 100 kHz bandwidth each, covering an effective range of velocities of 750 km s^{-1} , and allowing a resolution in velocity of 25 km s^{-1} . Secondly, a bank of 56 filters 10 kHz wide each allowed, by shifting the frequency of the local oscillator, a total useful velocity coverage of 220 km s^{-1} with a 2 km s^{-1} resolution.

The survey of the region where the object is located has been carried out in two steps. During the first step and in order to find the spatial extension and the velocity range covered by the object we observed the region delimited by $6^\circ \leq l \leq 10^\circ$ and $-7^\circ \leq b \leq -2^\circ$, in a $1^\circ \times 1^\circ$ grid using the wide-band filters. Each point has been observed once, integration time was 6 min. Since the system temperature is 250 K, the minimum detectable temperature at each channel was 0.02 K. Nevertheless, due to the existence of long period instabilities in the gain of the receptor which then shows up in the base line, we have experimentally determined the minimum detectable temperature to be about 0.15 K. We have covered the velocity range -450 to $+300 \text{ km s}^{-1}$. This first step of our survey did allow a preliminary determination of the spatial extension of the object as well as the velocity range covered by it.

We then carried out the second survey using the narrow band filters in order to improve the velocity resolution of the observations. A total of 55 points have been observed covering the region $7^\circ \leq l \leq 10^\circ$ and $-7^\circ \leq b \leq -2^\circ$ using a variable grid (Figure 2). Each point has been observed at least four times on different dates. On the average the overall integration time was 100 min, allowing a minimum detectable temperature of about 0.15 K.

In order to avoid baseline deformations due to long period fluctuations in the gain, calibrations were taken at time intervals not exceeding one hour. The South Celestial Pole has been used for this purpose. The temperature of the peak was taken to be 34.4 K, according to the calibration points published by Pöppel and Vieira (1973). The baseline was established by subtracting a profile, arbitrarily taken as showing no hydrogen, from each of the observed profiles. This profile has been observed during each calibration. As our hydrogenless profile we have taken that belonging to the coordinates $l=12^\circ$, $b=-6^\circ$. Observations have shown that no hydrogen emission exceeding $T_b=0.15 \text{ K}$ exists in this direction within the velocity range -150 to -350 km s^{-1} . Should this not be true, we would have obtained profiles showing systematically negative brightness temperatures.

3. Description of the Results

In Figure 1 we show an example of a profile in the direction $l=8.0^\circ$, $b=-5.5^\circ$, where high velocity neutral hydrogen has been detected. Table I contains the relevant data for each of the 26 points where the hydrogen line has been detected. Column (1) shows the galactic coordinates, (2) the radial velocity of the center of mass of the profile, V_{cm} , (3) the velocity dispersion σ , and (4) the hydrogen column density N_H . To calcu-

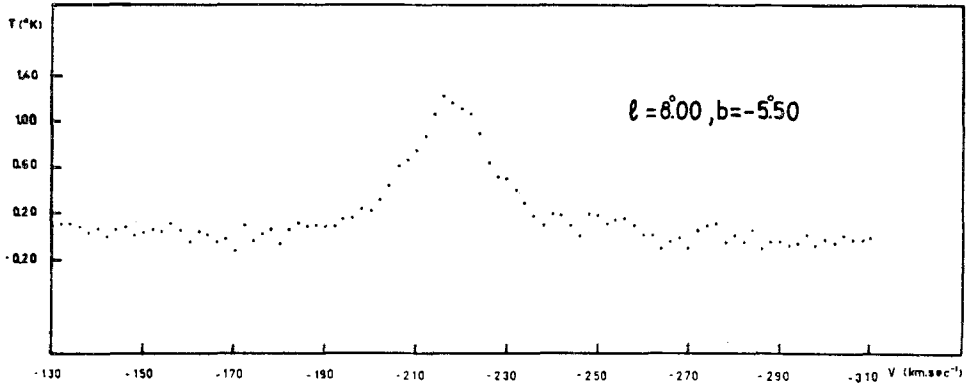

 Fig. 1. 21 cm hydrogen line profile for $l=8^{\circ}00$, $b=-5^{\circ}50$.

TABLE I
Summary of the Results

l ($^{\circ}$)	b ($^{\circ}$)	V_{cm} (km s^{-1})	σ (km s^{-1})	N_{H} (10^{18} at cm^{-2})
8.00	-3.00	-232.0	4.7	3.9
9.00	-3.00	-242.0	7.5	8.3
8.50	-3.50	-210.3	16.2	40.4
9.00	-3.50	-207.8	9.1	23.2
8.00	-4.00	-215.8	7.9	9.2
8.50	-4.00	-209.1	6.4	9.0
8.00	-4.50	-205.4	12.0	25.9
7.75	-4.75	-211.1	7.7	24.1
8.00	-4.75	-207.6	6.3	21.9
8.25	-4.75	-216.1	10.5	25.5
8.00	-5.00	-206.4	8.8	28.5
8.25	-5.00	-202.3	13.0	57.6
8.50	-5.00	-204.5	11.5	14.9
9.00	-5.00	-204.5	3.9	5.2
7.75	-5.25	-214.9	12.2	46.1
8.00	-5.25	-208.9	12.7	62.4
8.25	-5.25	-211.6	11.9	46.4
7.50	-5.50	-212.8	10.5	34.2
7.75	-5.50	-213.8	12.9	60.7
8.00	-5.50	-217.9	14.2	56.4
8.25	-5.50	-222.7	8.6	23.9
8.00	-5.75	-215.5	10.7	37.4
7.00	-6.00	-230.2	6.1	13.5
7.50	-6.00	-219.6	5.2	6.6
8.00	-6.00	-205.1	5.0	5.6
7.50	-6.50	-216.6	5.9	6.3

Column 1 gives the galactic coordinates of the observed profiles. Columns 2 to 4 show the physical characteristic of each profile. (2) radial velocity of the center of mass V_{cm} , (3) dispersion in radial velocity σ , (4) hydrogen column density N_{H} .

late V_{cm} we used the equation

$$V_{cm} = \frac{\sum_i T_{b_i} V_i}{\sum_i T_{b_i}}, \quad (1)$$

where T_{b_i} is the brightness temperature corresponding to radial velocity V_i . The velocity dispersion for each profile has been computed by means of the equation

$$\sigma = \frac{\sum_i T_{b_i} (V_{cm} - V_i)^2}{\sum_i T_{b_i}}. \quad (2)$$

We have assumed small optical depth, and therefore used the equation

$$N_H = 1.822 \cdot 10^{18} \int T_b dV \quad (3)$$

to compute N_H .

In Figure 2, we show the integrated brightness contours in units of 10^{18} atoms cm^{-2} .

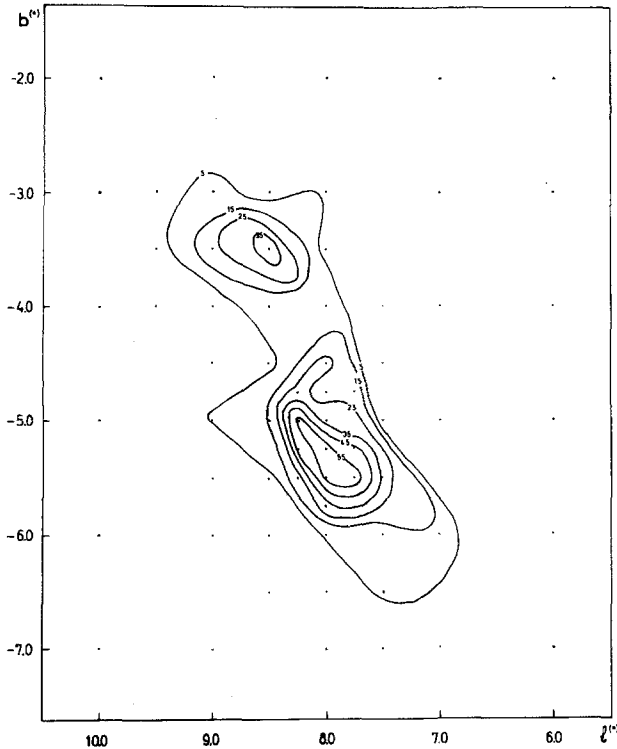


Fig. 2. The integrated brightness contours of the observed feature. Units of N_H are in 10^{18} atoms cm^{-2} . The dots indicate points observed during the survey.

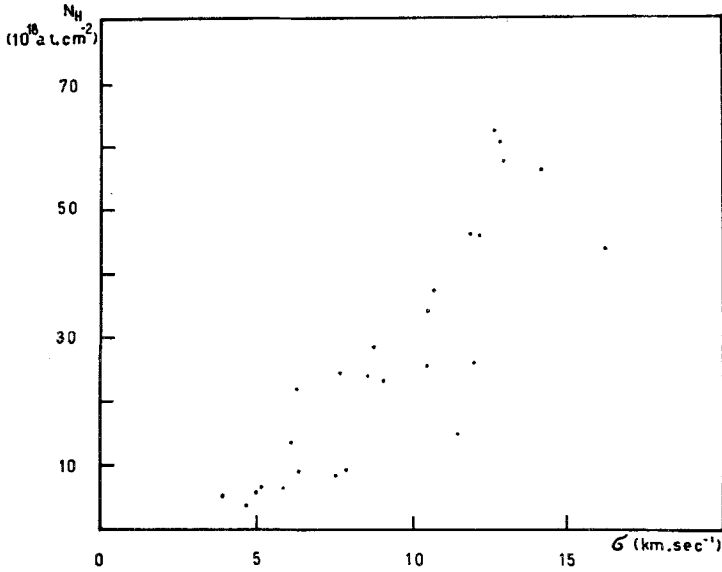


Fig. 3. The N_H vs. σ correlation. The correlation coefficient is 0.85.

The dots indicate points observed during the survey. The object is elongated in shape and shows two concentrations; a major and a secondary one. The major concentration is calculated to have a mass of

$$M_1 = 130R^2(\text{kpc})M_\odot, \tag{4}$$

and the secondary concentration

$$M_2 = 60R^2(\text{kpc})M_\odot \tag{5}$$

The object has a total mass of $190R^2(\text{kpc})M_\odot$. The error in the determination of the masses is estimated to be about 15%.

We have looked for possible correlations between the quantities N_H , V_{cm} and σ . We have found obvious correlation between the values of N_H and σ only. This is shown in Figure 3. The linear correlation coefficient, as defined by Bevington (1969), was found to be 0.85 with the probability of chance correlation being about 10^{-6} . Errors in the value of σ are estimated to vary between $\pm 1.0 \text{ km s}^{-1}$ and $\pm 2.0 \text{ km s}^{-1}$. Although the error is dependent on N_H^{-1} , we could not discover any systematic error which could substantially influence the correlation of N_H and σ .

Before we discuss possible interpretations of the nature of the object it will be convenient to define some characteristic parameters as a function of its distance to the Sun. We make use of (4) and (5) to eliminate the mass from the equations. In order to simplify our analysis we approximate both the major and the secondary concentrations by spheroids of radius

$$r = R(\varphi_1\varphi_2)^{1/2}, \tag{6}$$

where φ_1 and φ_2 are the apparent angular radii of the major and minor axes, respectively.

We define: (a) The kinetic energy of translation for the entire structure

$$E_{k_{tr}} = \frac{1}{2} M \bar{V}_{cm}^2 \sim 8.6 \times 10^{49} R^2 (\text{kpc}) \text{ ergs}, \quad (7)$$

where

$$\bar{V}_{cm} = \frac{\sum_i N_{H_i} V_{cm_i}}{\sum_i N_{H_i}} = -212.3 \text{ km s}^{-1} \quad (8)$$

is the mean weighted radial velocity with respect to the LSR.

(b) The internal kinetic energy for the entire structure

$$E_{k_{int}} = \frac{3}{2} \sum_i M_i (\sigma_i^2 + V_{r_i}^2) \sim 8.7 \times 10^{47} R^2 (\text{kpc}) \text{ ergs}, \quad (9)$$

where

$$V_{r_i} = V_{cm_i} - \bar{V}_{cm}. \quad (10)$$

(c) The internal gravitational energy for the major and secondary concentrations

$$E_{g_{int}} = -\frac{3}{5} G \frac{M^2}{r}. \quad (11)$$

The radius r of the spheroids corresponding to the major and secondary concentrations are

$$r_1 = 0.014R(\text{kpc}), \quad (12)$$

$$r_2 = 0.010R(\text{kpc}), \quad (13)$$

respectively. We then have

$$E_{g_{int_1}} = -6.3 \times 10^{43} R^3 (\text{kpc}) \text{ ergs}, \quad (14)$$

$$E_{g_{int_2}} = -1.9 \times 10^{43} R^3 (\text{kpc}) \text{ ergs}. \quad (15)$$

(d) The mean density for the major and secondary concentrations

$$\begin{aligned} \bar{\rho}_1 &= \frac{M_1}{4/3r_1^3} \sim 8 \times 10^{-25} R^{-1} (\text{kpc}) \text{ gr cm}^{-3} \sim \\ &\sim 0.5R^{-1} (\text{kpc}) \text{ atoms cm}^{-3}, \end{aligned} \quad (16)$$

$$\bar{\rho}_2 = \frac{M_2}{4/3r_2^3} \sim 10 \times 10^{-25} R^{-1} (\text{kpc}) \text{ gr cm}^{-3} \sim 0.6R^{-1} (\text{kpc}) \text{ atoms cm}^{-3} \quad (17)$$

(e) The characteristic time for the evolution of the entire structure

$$\bar{\sigma} = \frac{\bar{r}}{0.5\bar{\sigma}} \sim 2.5 \times 10^6 R(\text{kpc}) \text{ yrs}, \quad (18)$$

with

$$\bar{\sigma} = \frac{\sum_i N_{\text{H}_i} \sigma_i}{\sum_i N_{\text{H}_i}} = 11.2 \pm 1.0 \text{ km s}^{-1}. \quad (19)$$

COMPARISON WITH OBSERVATIONS BY SARABER AND SHANE

Although the observations at Parque Pereyra and at Dwingeloo have been carried out with instruments of similar characteristics, the results show some differences. Firstly, comparing our Figure 2 with Figure 1 from Saraber and Shane, we see that both show a similar spatial extension for the object, as well as the two distinct concentrations. Nevertheless our observations show a major and a secondary concentration of different masses. In Table II, we compare some parameters resulting from both sets of observations. The differences in the estimates of the total mass, mean density and mean velocity dispersion are obviously substantial. The values based on the Dwingeloo observations exceeded our estimated mass in 62% and in 34% our value for σ . These figures are much higher than the calculated errors of our parameters. The difference in the masses is excessively high to be attributed to a discrepancy in the temperature scale. The difference in the values of σ is again too large to be due to the fact that our observations were taken with a frequency resolution of 10 kHz, while the resolution at Dwingeloo is only 16 kHz. Very likely, the main reason for the differences can be attributed to the fact that the Dwingeloo observations require a correction of the zero level as a function of the altitude, which turns out to be important close to the horizon. In a previous work, Mirabel *et al.* (1975) have found that for weak objects the esti-

TABLE II

The Parameters of the Object Obtained on the Basis of the Observations at Parque Pereyra and Dwingeloo

	Mirabel-Franco (Parque Pereyra)	Saraber-Shane (Dwingeloo)
Size ^a	principal concentration $r_1=0.8$ secondary concentration $r_2=0.6$	$r=1.0$
Mean weighted radial velocity	$-212.3 \pm 1.0 \text{ km s}^{-1}$	-212.8 km s^{-1}
Velocity dispersion	$11.2 \pm 1.0 \text{ km s}^{-1}$	15 km s^{-1}
Hi total mass	$190 \pm 28 R^2(\text{kpc})$ solar masses	$307 R^2(\text{kpc})$ solar masses
Hi density ^b	$0.55 R^{-1}(\text{kpc})$ atoms cm^{-3}	$0.90 R^{-1}(\text{kpc})$ atoms cm^{-3}

(a) Assuming spherical shape.

(b) Mean values corresponding to the density of the principal and secondary concentrations.

mates of N_{H} based on Dwingeloo observations, and close to the horizon of that observatory, are approximately 75% higher than those based on Parque Pereyra observations. A systematic error in the zero line of the Dwingeloo profiles could well explain the differences in both the total mass and the mean velocity dispersion, since the error in both observations is of the same sign. Based on our profiles we estimated that lowering our base line systematically by about 0.17 K would lead to an overestimate in the total mass of 62% and of 37% in σ .

4. Interpretation of the Results

As can be clearly seen from Table I, the radial velocity field shows large differences between a given point and the next one, but it does not exhibit any systematic behaviour which would allow us to assume that the velocity gradient is due to either transverse motions or overall rotation of the structure. We may therefore assume that the velocity gradient originates mainly in the turbulent motions of the gas forming the structure.

If we assume that the gas is spherically distributed in space, the linear correlation between N_{H} and σ leads us naturally to interpret it as an expanding cloud. It can be shown by purely geometrical arguments that, in such a case, the equation relating N_{H} and σ is of the form

$$N_{\text{H}} = \frac{\alpha \bar{\rho} r}{V_{\text{exp}}} \sigma, \quad (20)$$

where $\bar{\rho}$ is the mean density of the gas; r , the radius of the sphere; V_{exp} , the expansion velocity; and α is a constant.

We will now discuss several possible interpretations of the origin and nature of the object, assuming that the two concentrations are physically related. The following possibilities will be discussed:

- (a) An object close to the Sun.
- (b) An extragalactic object.
- (c) High-velocity Cloud penetrating the galactic disc.
- (d) High-velocity Cloud in orbit about the Galaxy.
- (e) The cloud forms part of the Magellanic Stream.
- (f) The cloud was expelled from the galactic nucleus.

(a) An object which originated close to the Sun and which shows such highly anomalous velocity could be produced only as the result of an explosive event. We assume, therefore, that the object is a SNR. Taking into account that the energy released in the course of a type II supernova explosion is of the order of 10^{51} ergs (Woltjer, 1972), according to Equation (7), the object should be located at a distance $R \leq 3.4$ kpc. In the case that we should deal with a shell, the upper limit should be less, because the total mass of HI implied is larger than that considered here. Several arguments can be put forward against this interpretation:

(i) No nonthermal radiosource appears close to the region in the Ilovaisky and Lequeux (1972) catalogue.

(ii) An inspection of the 21 cm line survey published by Kerr (1969) reveals no conspicuous absence of low velocity gas at galactic longitudes corresponding to the object, as would be expected in case of a local explosion.

Further, no gas with high positive velocities has been detected during our first low velocity resolution survey in this direction.

(iii) The Palomar Sky Survey plates do not allow an identification of this structure with any nearby optical object.

(b) There are three arguments against the interpretation of our object as a galaxy:

(i) Whatever the nature of the object the correlation between N_{H} and σ indicates that it cannot be considered in an equilibrium state, but rather it must be in expansion. We may then take

$$2E_{k_{\text{int}}} > E_{g_{\text{int}}}. \quad (21)$$

Letting q to be the ratio between the total mass and the hydrogen mass, and making use of relations (9), (14) and (15) we obtain an upper limit for the distance

$$R < 20q^{-1} \text{ Mpc}. \quad (22)$$

Assuming that we are dealing with a galaxy, we may take $q > 10$, which in turn implies that its distance must be less than 2 Mpc, and therefore very likely it should belong to the Local Group. In this case the distance between the two concentrations should be less than 70 kpc. On the other hand, the galactocentric velocity of the object is -247 km s^{-1} , larger than the escape velocity from the Local Group, in direct contradiction with the upper limit for its distance.

(ii) Dynamical arguments would place this object at a distance of less than 2 Mpc. Nevertheless, we could not identify optically the object on any of the Palomar plates.

(iii) A galaxy at a distance of less than 2 Mpc should be easily detectable in the continuum. No relation of the 21 cm line emission of the object to known radio sources could be found.

(c) According to Oort (1967) some of the high-velocity HI clouds may consist of intergalactic matter penetrating the galactic disk. The asymmetrical distribution of the HVC's in space, as well as in velocity would be a consequence of the solar motion and of the systemic motion of the Galaxy towards a point on the second quadrant and at positive latitudes. This would then explain the high concentration of HVC's with negative velocities at that region. According to this hypothesis one would expect to encounter positive radial velocities at the location of our object. The observations show that the velocity of our object is of precisely the opposite sign, making this hypothesis highly unlikely.

(d) We will now consider the hypothesis according to which the HVC's are extragalactic objects, orbiting the Galaxy (Kerr and Sullivan, 1969). Assuming highly elliptical orbits around the Galaxy, a sinusoidal relation exists between galactocentric

velocity and galactic longitude. This relation has been published by Verschuur (1969, Figure 3), where our object is shown along with the HVC's and the galaxies belonging to the Local Group known at the time. While the radial velocity of the objects belonging to the Local Group is positive over the range of longitudes which concerns us, our object shows a high, negative velocity. This fact allows us to reject this hypothesis.

(e) The recently discovered Magellanic Stream (MS), (Mathewson, Cleary and Murray, 1974) extends from the vicinity of the Magellanic Clouds past the South Galactic Pole to the region $l=90^\circ$, $b=-35^\circ$. Although the discovery of the MS did permit the identification of the origin of many HVC's of the southern galactic hemisphere, this is not the case for the structure studied here. Indeed, its great angular distance ($d > 80^\circ$) to the MS, as well as its large difference in galactocentric velocity ($\sim 120 \text{ km s}^{-1}$) with respect to the structures belonging to the Stream which are located at the same galactic longitude makes this interpretation about the origin of the object highly unlikely.

(f) The neutral hydrogen surveys close to the galactic center and outside the plane did permit the discovery of several structures with anomalous velocities (van der Kruit, 1970; Sanders *et al.*, 1972; Mirabel and Turner, 1975). The observations show that at forbidden velocities the high velocity hydrogen has a tilted structure. At the positive longitudes, where negative velocities are forbidden, the hydrogen is found at negative latitudes. On the other hand at negative longitudes, where the positive velocities are forbidden, it is usually found at positive latitudes. Our object confirms this picture of a generally tilted structure.

These objects are usually interpreted as having been ejected from the galactic nucleus as a consequence of recurring explosive activity taking place there. Assuming that the object is located at a distance of 10 kpc and that its velocity has been constant since its ejection from the galactic nucleus, 6×10^6 years are required to reach its present position. Such a value is consistent with the period of 5×10^6 years given by Saraber and Shane, on the basis of van der Kruit's model (1971). On the other hand we have shown that the structure might be in an expanding state. On the basis of a purely geometrical model we may estimate the mean value of the constant α in Equation (20), by making use of the 21 cm profiles. Thus we find

$$V_{\text{exp}} = \frac{5.4\bar{\varrho}\bar{r}}{tg\beta}, \quad (23)$$

where β is the slope of the regression line in the N_{H} vs. σ relation, and $\bar{\varrho}$ and \bar{r} are the mean values based on those which we obtained before for the two concentrations. From Equation (23) we obtained $V_{\text{exp}} \sim 20 \text{ km s}^{-1}$. If we assume now that the expansion velocity remained constant from the time of the ejection, the time interval required for the structure to reach its present dimensions is calculated to be 6×10^6 years, about the same as the time necessary for it to reach its present position, starting from the galactic nucleus.

Under the same hypothesis the initial density of the gas must have been several

orders of magnitude larger than its present density. This result agrees well with one of the basic assumptions of van der Kruit's model. According to him the objects ejected from the galactic nucleus must initially be very dense (10^3 to 10^4 atoms cm^{-3}).

Based on the galactocentric velocity of the object we estimated a lower limit for the energy of its ejection at about 10^{52} ergs.

5. Conclusions

Our observations agree with those of Saraber and Shane on the spatial extension and the existence of two concentrations in the complex structure studied. Our values for several of the characteristic parameters of the object differ however significantly from those obtained by these authors. The observations also show a linear correlation between N_{H} and σ , which indicates that the object is expanding. An analysis of the different possible interpretations on the nature of the object makes us conclude that very likely we are dealing with an ejecta from the galactic nucleus. The object thus constitutes another evidence for the exploding activity of the nucleus. The physical characteristic of the object indicates that the explosion giving place to its ejection must have involved an energy greater than 10^{52} ergs. The age of the structure is estimated to be about 6×10^6 years. The initial density of the gas must have exceeded by several orders of magnitude the presently observed value.

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