Bull. Spec. Astrophys. Obs., 2000, 49, 20-31

Neutral hydrogen distribution in the vicinity of the supernova remnant Cygnus Loop

I.V. Gosachinskij

St.-Petersburg branch of the Special Astrophysical Observatory,
Pulkovskoe shosse 65, St.-Petersburg, 196140, gos@fsao.spb.su

Received October 1, 1999; accepted March 31, 2000.

Abstract. Interstellar neutral hydrogen distribution within $13° \times 10°$ around the supernova remnant Cygnus Loop is studied by high angular resolution 21 cm line observations on the radio telescope RATAN-600. The geometry of the cavity, inside which this supernova exploded, was investigated in detail for the first time and it also was shown, that the cavity could not be formed by a stellar wind of a progenitor star, hence it is a part of a normal structure of galactic gas. Details of HI with large negative radial velocities, which could be connected to the supernova remnant, are not revealed.

Key words: ISM: individual: Cygnus Loop – ISM: supernova remnants

1. Introduction

The supernova remnant Cygnus Loop (G74.0–8.5) is a typical middle-aged (10 – 15 thousand years) shell remnant. The comparative proximity to the Sun (750 pc) and the large angular size ($\simeq 3°$) allow effective studies of its structure in all accessible ranges of wavelengths: in radio (continuum and polarization) – Leahy et al. (1997), in IR – Arendt et al. (1992), in various lines of the optical range – Levenson et al. (1998) and in the X-ray range – Levenson et al. (1997) to be carried out. There are tens of other references which were mentioned in the papers cited herein because this object has gained extraordinary popularity since the time of its first researches, Hubble (1937), Oort (1946) and Minkovski (1958). It is considered, according to the generally accepted idea of McCray and Snow (1979), that this supernova has exploded inside a practically empty cavity of interstellar gas and only about 1000 years ago its blast wave hit denser "walls" of this cavity and a process of emission in optical wave range began. Within the framework of this model it is possible to explain coexistence in the same environment of regions of X-ray radiation with a temperature of $\simeq 10^6$ K (i.e. the presence of a fast nonradiative shock wave) and areas of bright radiation of optical lines requiring a strong deceleration of the shock wave and beginning of radiation of its energy.

The origin of this cavity is not quite clear. There is a natural assumption that such a cavity may be created by a stellar wind. Certainly, any star–progenitor of a supernova during its life on the main sequence sweeps away the surrounding gas by the wind. Such cavities around some young supernova remnants were found from the HI environments bordering on them, and the kinematics of these environments shows that, firstly, they are much older than the remnants occurring inside them and, secondly, the wind power of a single star suffices to form the observed cavities (Gosachinskij & Khersonskij, 1987a,b, 1988). Therefore to solve this problem it is necessary to investigate carefully the undisturbed gas in the vicinity of the remnant for the purpose of finding attributes of the structure. Best suited to this purpose is the line of neutral hydrogen at 21 cm wavelength, the molecule lines, especially CO, and observations of dust in the IR. Unfortunately, the studies in these fields are insufficient.

Neutral hydrogen at 21 cm wavelength in the vicinity of the Cygnus Loop has been investigated to the fullest extent in the work of DeNoyer (1975). She has shown that no expanding HI envelope around the Cygnus Loop is observed (which was naturally to be expected at velocities of the shock wave, ~ 200 km/s), but some hint at the relation of HI filaments at velocities of -40 to -60 km/s with the remnant is present. It should be noted that in this work the angular resolution was not too high, 0.16°, and besides, the author did not take the trouble at all to separate objects of small angular size, which could be connected with the supernova remnant, from the galactic background of the HI emission line. The absence of high-velocity HI gas in the Cygnus Loop was confirmed with a higher angular resolution, 3.3′, in the paper by Giovanelli and Haynes (1979).

Payne and Bania (1979) have tried with the help of the HI absorption line to find connection of the variable point source CL4 projected onto the disk of the remnant with the remnant itself. However this attempt should be recognized unsuccessful, as in this region the kinematic distances are useless because of the small value of the derivative dv/dr. At last, Koo and Heiles (1991) in a comprehensive search for high-velocity HI details in many supernova remnants have not found anything interesting in the Cygnus Loop.

Scoville et al. (1977) have found two clouds of CO in the immediate proximity of the western arch of optical emission of the remnant. These clouds are well visible also in the review of the CO line of Dame et al. (1987), the results of which are accessible in the database in Strassburg, ADS. On the basis of these data Tenorio-Tagle et al. (1985) have calculated a two-dimensional model of collision of the shock wave of the remnant with the molecular cloud which explains, in their opinion, the large-scale structure of the Cygnus Loop.

In the IR range, two large papers were devoted to studies of the vicinity of the Cygnus Loop on the basis of IRAS data: Braun and Strom (1986) and Arendt et al. (1992). Although the authors were more interested in IR emission of the remnant itself than of the environmental material, nevertheless, in both papers a cloud of cold (undisturbed) dust to the west of the remnant is noted, which is connected apparently with the molecular cloud spoken above. Let us note, that the authors of the latter paper have accurately removed the background IR emission that is not associated with the supernova remnant, so their data on the dust structure in the vicinity of the remnant are reliable enough.

The high angular resolution of the radio telescope RATAN–600 and its good sensitivity to low-contrast details of the distribution of brightness have allowed us to obtain a complete enough picture of the structure of undisturbed interstellar medium from radiation of the HI line at 21 cm wavelength in the vicinity of the Cygnus Loop. The results are presented herein.

2. Equipment and reduction

For investigation of the distribution of neutral hydrogen in the field of the supernova remnant Cygnus Loop 20 cross-sections in right ascension were obtained with the radio telescope RATAN–600 through $0.6°$ in declination in the range $+25.0° < \delta < 36.9°$, from which a region of right ascensions $20^h10^m < \alpha < 21^h15^m$ was chosen. The detailed description of the equipment, technique of observations and processing is available in the paper by Gosachinskij and Lozinskaya (1997).

In this range of elevation the beam of the radio telescope RATAN–600 at the 21 cm wavelength has an angular size of $2' \times 12'$, effective area of 875 m^2, and rather significant losses in brightness temperature — up to 30 %. The latter are due to the properties of the design of the antenna and to the fact that the observations were carried out at rather large elevations. The system noise temperature was $\approx$ 60 K, the 39-channel filter bank spectrum analyzer has a channel width of 30 kHz (6.3 km/s). The cross-section in each declination consists of two series with three drift curves each, obtained so that the adjustment of the receiver was shifted by half of the channel width, so, as a result, each cross-section has 78 channels following through 3.15 km/s. Such a procedure of observations allows also effective cleaning of interferences to be carried out. The average rms noise fluctuations in spectral channels in the final records was 0.2 K. Parameters of the antenna and equipment were checked in each cycle of observations with the help of measurements of a series of reference sources (see Venger et al., 1979). An example of complete cross-section in declination $+35°$ is presented in Fig. 1. The left numbers on the curves are the spectral channel numbers, on the right is the radial velocities relative to the Local standard of rest. In the left lower corner the scale of antenna temperatures is given.

In the further processing the extended background of HI emission was subtracted from the drift curves in each spectral channel with the help of spline-interpolation to the bottom level of distribution of brightness of HI; then the curves containing only details of rather small angular size were processed. An example is represented in Fig. 2.

The excluded background part of the drift curves contain: a) large-scale details of the distribution of radiation of interstellar gas, such as spiral arms or huge complexes; b) the radiation of structureless intercloud medium, if it exists; c) details of small angular size unresolved by the beam of the radio telescope; d) spurious large-scale background signal arising because of the presence of far side lobes and field of scattering of the antenna beam. One should note, that the extraction of the background components in the fashion mentioned above may result in some underestimation of brightness and angular size of the remaining small-scale details owing to the uncertainty in the zero level of the difference drift scans. Parameters of the details (coordinates, angular sizes and antenna temperature) were determined with the help of the programme of Gauss-analysis.

The errors of the measured parameters have the following values. The radial velocity of an isolated detail HI with the average value of brightness is measured with an accuracy of $\pm$ 1 km/s. In some special

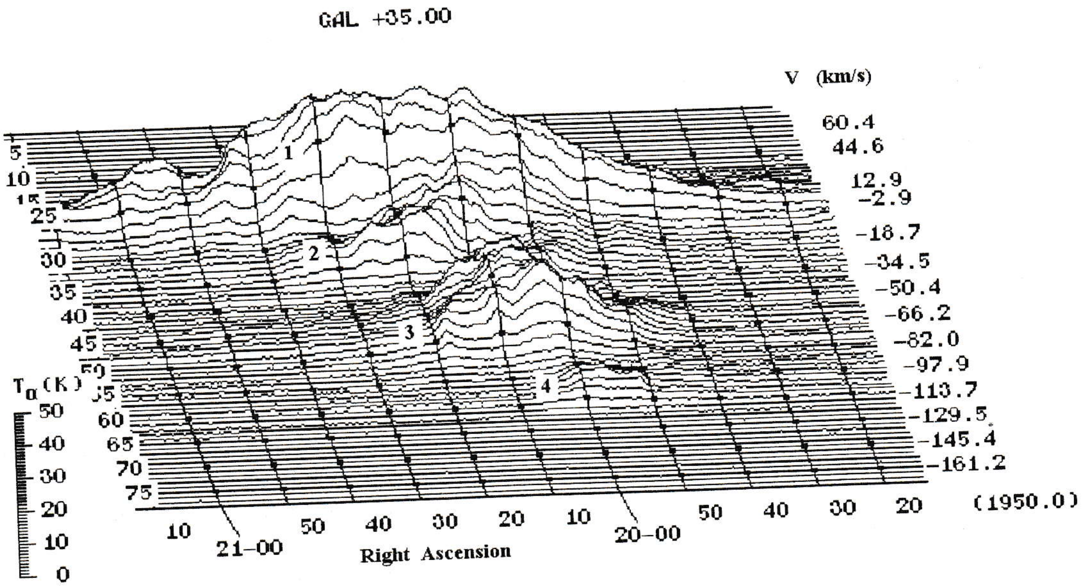

Figure 1: *Cross-section along right ascension through the Galactic plane obtained with the RATAN–600 at Declination* +35°.

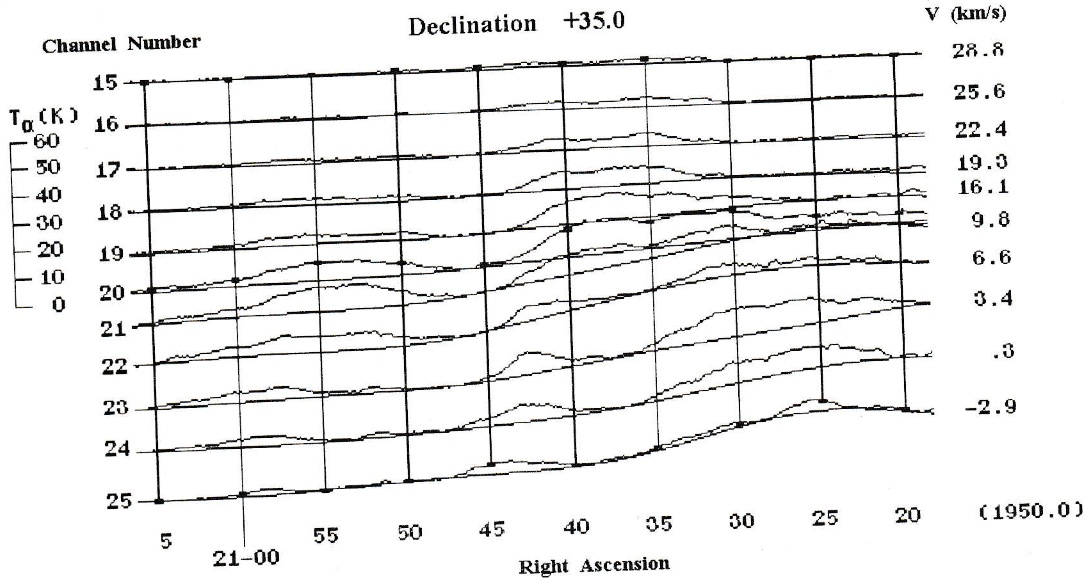

Figure 2: *Spline-interpolation of HI background emission in some spectral channels of cross-section* $\delta = +35°$ *(spline curves are lower curves of each pair).*

cases noted below, the accuracy is worse because of the difficulties in separation of the object from the background or from the neighbouring details. The error of measurement of the brightness temperatures is approximately 0.4 K in view of antenna calibration errors. The error of estimation of the angular sizes in right ascension is 0.1°. In the latter case the same stipulations as for radial velocities are valid. In declination, the resolution of the antenna is much lower, than in right ascension and, accordingly, the accuracy of measurement of angular sizes is worse.

The accuracy of estimation of distances depends on the method of their determination and in each case should be examined separately. To the details of HI the kinematic distance is usually applied. They are determined from HI radial velocities and any acceptable model of galactic rotation (for example, see paper of Kerr and Linden Bell, 1986). However, as we have already mentioned, in the region of galactic longitudes considered and at radial velocities from –20 to +40 km/s the value of dv/dr is small, but in addition, at positive radial velocities there exists also an ambiguity of measuring the distance. So the emission of gas at distances of 0 to 6 kpc from the Sun falls within the range of radial velocities indicated. As a result, if there are no estimates from other reasonings, it is extremely problematic to compare the HI details with other objects of this region, and the accuracy of evaluation of HI masses appears to be no better than 0.5–1 order of magnitude.

3. Results and discussion

3.1. Spiral arms in the region of Cygnus Loop

The general distribution of neutral hydrogen vrs radial velocities in the constellation Cygnus is well visible in Fig. 1. The cross-section in declination +35°, which is at the edge of the region in question is given here. All gas can be divided as a minimum into four components: 1) at radial velocities around zero, the main maximum of emission is the sum of the extended component near the Sun and the spiral arm Orion–Cygnus up to 5–6 kpc from the Sun; 2) between −10 to −50 km/s is located an interarm bridge of Orion–Cygnus and Perseus which is seen at distances of about 7 kpc; 3) the Perseus spiral arm has radial velocities from −50 to −90 km/s and distances from 9 to 11 kpc; 4) and, at last, from −90 to −120 km/s the so-called "external" spiral arm is observed at a distance of about 13 kpc from the Sun.

This structure of galactic gas is better defined in Fig. 3, where the components of the HI profiles are isolated with the help of the programme of Gauss-analysis. Note that each component has its characteristic distribution over the galactic latitude, besides a general rise of the layer of gas to the north of the plane of the Galaxy is observed in this area, so, as the Cygnus Loop has a rather large negative latitude, two external spiral arms are practically not visible here (see Fig. 3b).

In searching for the details of the surrounding gas, which could be related to the supernova remnant, the evaluation of the average radial velocity of the remnant is needed. However this estimate is rather difficult to make, since the greater part of radiating matter is disturbed by the shock wave. From the data of the paper by Minkowski (1958) Cygnus Loop expands at a velocity of 116 km/s relative to the centre and at +33 km/s relative to the local standard of rest. Further it was found (see Levenson et al., 1998), that such a speed of expansion is characteristic only of a radiative shock wave in dense regions with bright optical emission. In the region of X–ray radiation, the velocity of the shock wave reaches 400 km/s.

Greidanus and Strom (1992) have found a narrow component of the forbidden line [O III] λ5007 Å, which, as they believe, arises in the field of photoionization before the main shock wave. This has allowed them to estimate the radial velocity of the remnant as a whole at 8 ± 3 km/s. Certainly, the formal kinematic distance of 1.3 ± 0.7 kpc given by them makes no essential sense as we pointed out above. Anyway it is obvious, that the surrounding interstellar gas has radial velocities about 0 km/s, i.e. it is contained in the main emission maximum of the HI line in Fig. 3.

3.2. Neutral hydrogen at positive radial velocities

The details of the HI luminosity distribution obtained by means of processing of the drift curves with the radio telescope RATAN-600 are presented at different radial velocities in Figs. 4–8.

Right ascension and declination (given below and at the right in each curve) are of epoch 1950.0, radial velocities — relative to the Local standard of rest. The scale of antenna temperatures is given at the left in each figure. The details of HI emission are shown as grey shading on each drift curve. These details were joined in supposed HI structures extended in declination by tnin lines. The ring fibrous structure shown in black at the center of each figure is a schematic of the supernova remnant, mainly from the optical data, and in the region of the southern salient from the data of radio observations.

For completeness of the pattern one has to examine the details of HI at positive radial velocities too, which is useful in the case the estimate of Minkowski (1958) is valid. In Fig. 3 it can be seen that in the field of the supernova remnant at radial velocities over 30 km/s the emission of background neutral hydrogen is very weak. It is confirmed also by Fig. 4 where the isolation of small-scale HI details is given in the field of the supernova remnant at radial velocities +30 and +35 km/s. Rather faint HI clouds observed here have not any morphological indications of connection with the expanding remnant, especially with its north-east arc, where the brightest radiation in optical lines is observed and, as it is believed, the interaction of the shock wave of the remnant with the wall of the cavity must occur. Therefore, this gas may be presumed to be not related to the area of the supernova remnant.

3.3. "Cavity" of interstellar gas around the supernova remnant

The location of HI details in the neighborhood of the supernova remnant Cygnus Loop at radial velocities of −10, 0 and + 10 km/s is given in Fig. 5. The designations of the features are the same as in Fig. 4, however the scale of antenna temperatures is diminished 3.3 times because in this region of radial velocities the emission of HI details is very bright. Note that outside of this range of radial velocities the emission of the structures indicated in Fig. 5 practically disappears.

It is obvious that in contrast to positive and high negative radial velocities the morphology of the HI

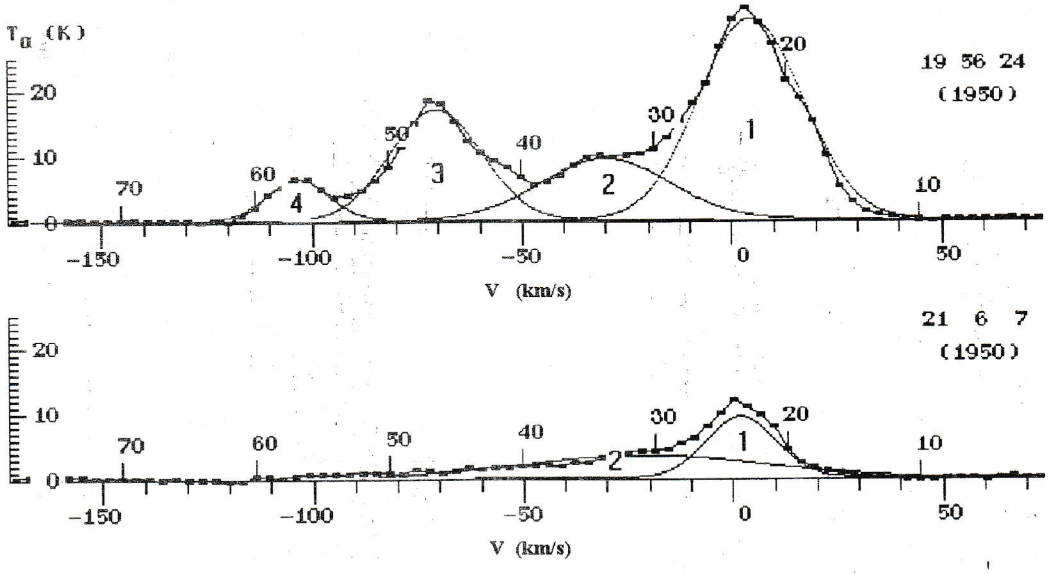

Figure 3: *Profiles of the HI line in declination +35°: near the plane of the Galaxy (a) and at latitude −8.5° (b). The components of the profiles are: 1 — gas with radial velocities about zero, 2 — interarm feature, 3 — Perseus arm, 4 — external arm.*

details in this figure is explicitly related to the supernova remnant Cygnus Loop. It should be borne in mind that, as we noted above, in this sector of the Galaxy the distribution of HI emission vrs radial velocities may not at all correspond to the location of the gas in space, and at certain velocities casual projection of HI clouds onto the supernova remnant details is possible. The conformity of the brightest north-east arc of the supernova remnant to the HI arcs at a radial velocity of 0 km/s with the centre at $\alpha = 21^h00^m$, which extends from $\delta = +25.6°$ to $\delta = +33.1°$ is most impressive. There is no doubt that it is this arc of neutral gas that represents the "wall" of the assumed cavity, in which the shock wave of the supernova remnant is spreading now. The western arc of the remnant most likely corresponds to the HI detail at the radial velocity +10 km/s. Note also, that south of the remnant, essential HI clouds are not observed, which allows the shock wave to spread rather freely in an empty medium.

The three-dimensional morphology of the cavity is difficult to represent. The distribution of HI at intermediate velocities, not presented in Fig. 5, shows these details represent a common structure also on the axis of radial velocities. However, it does not seem possible to estimate its extension along line of sight. If we assume that the HI cavity displayed in Fig. 5 really contains the supernova remnant, then for the distance of 750 pc from the Sun its apparent angular sizes correspond to the following linear dimensions: exterior 80 × 110 pc, interior 40 × 65 pc. The mean brightness temperature of the HI line in the cavity "wall" is about 12 K, which corresponds to the mean content of gas in the line of sight column, $2.2–4.4 \cdot 10^{21}$ cm^{-2}, with a half-width of the HI line profile of 10 – 20 km/s. If the extent of the "cavity" along the line of sight is about the same as in a picture plane, the concentration of gas will then turn out to be 0.7–1.5 cm^{-3}, and the total mass $1.5 - 3.3 \cdot 10^4 M_\odot$.

One should also note some morphological features of the "cavity", which may shed light on its nature. First, it is complete absence of indications of large-scale radial motion of gas in the cavity "walls", and, second, a considerable north-south prolateness of the "cavity". This suggests that the "cavity" is a part of the natural structure of galactic gas but not associated with the wind of the progenitor star.

3.4. Neutral hydrogen at high negative radial velocities

In the paper of DeNoyer (1975) the presence of HI details in the region of Cygnus Loop at radial velocities from −40 to −60 km/s is pointed out and their possible connection with the supernova remnant is discussed. The results of observations of HI details with RATAN-600 within −40 to −120 km/s are presented in Figs. 6 – 8. The designations and the scale of antenna temperatures are the same, as in Fig. 4. In this area there are many noticeable HI clouds; some of them are projected onto the disk of the supernova remnant. It is practically impossible to make a direct comparison of our data with DeNoyer's (1975), because the antenna beams of the used radio telescopes strongly differ in angular dimension and shape. Besides, as we indicated above, in the paper of DeNoyer

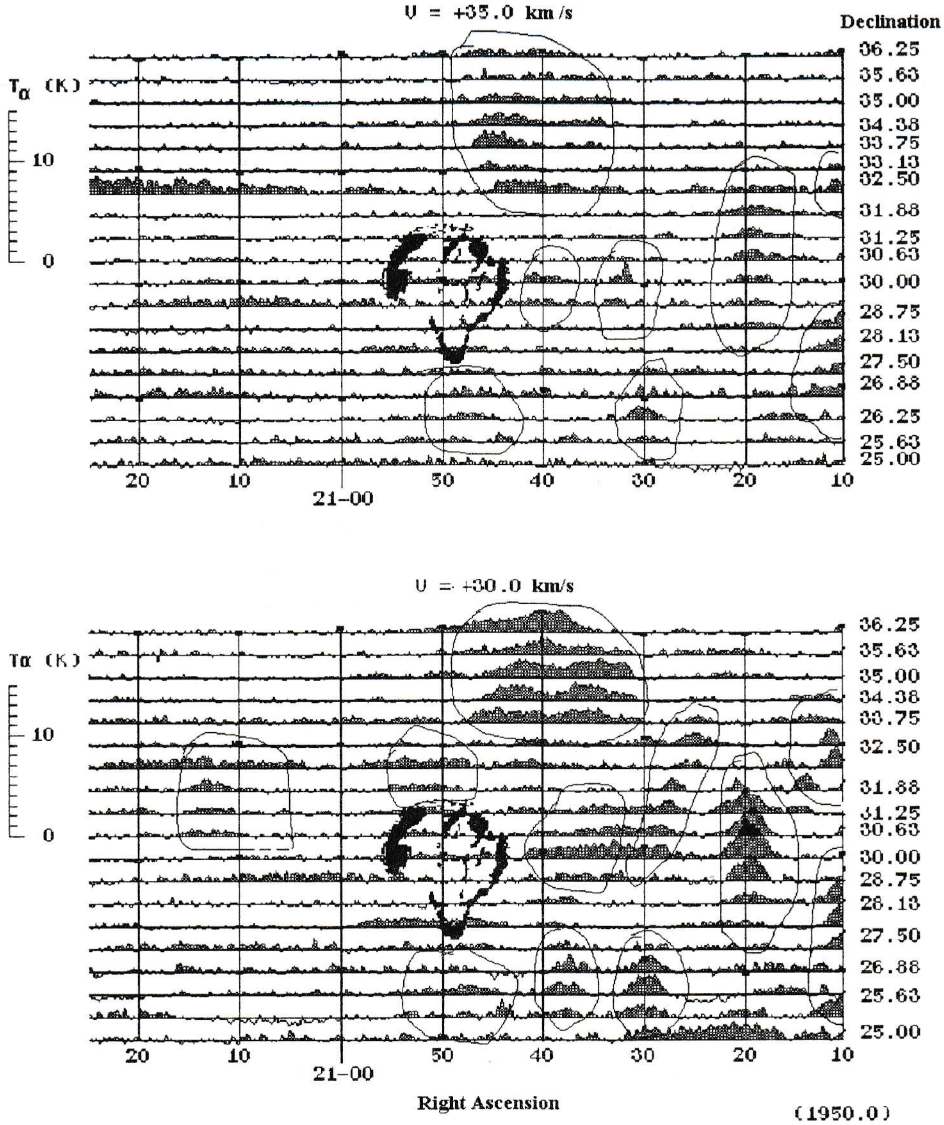

Figure 4: *Distribution of HI details in the neighborhood of the Cygnus Loop at radial velocities +30 and +35 km/s. Clouds and other HI structures are shown with light lines. In this and the following figures the HI details are shaded. Fibre structure at the centers of figures, in black, schematically displays the supernova remnant mainly under the optical data, and in the field of a southern salient via radio.*

(1975) the galactic background is not eliminated.

Despite the rather high galactic latitude of this supernova remnant a considerable number of HI clouds is seen in Figs. 6 – 8, though their luminosity is much lower, than at zero radial velocities. Keeping in mind what was said in Section 3.1 concerning the distribution of HI radiation in this region, which relates to the outer spiral arms, it is rather difficult to make a convincing inference about belonging of these clouds to a particular spiral arm and, therefore, about the distance of the clouds. The matter, as can be seen in Fig. 3, is that at these high negative radial velocities most likely radiates the gas located in the bridge between spiral arms of Orion – Cygnus and Perseus. This is surprising by itself, since requires unusually powerful intrinsic motions of gas clouds inside this structure remarkable for nothing more.

As to the relation of high-velocity gas to the supernova remnant Cygnus Loop, our observations, as well as the paper of DeNoyer (1975), confirm the pres-

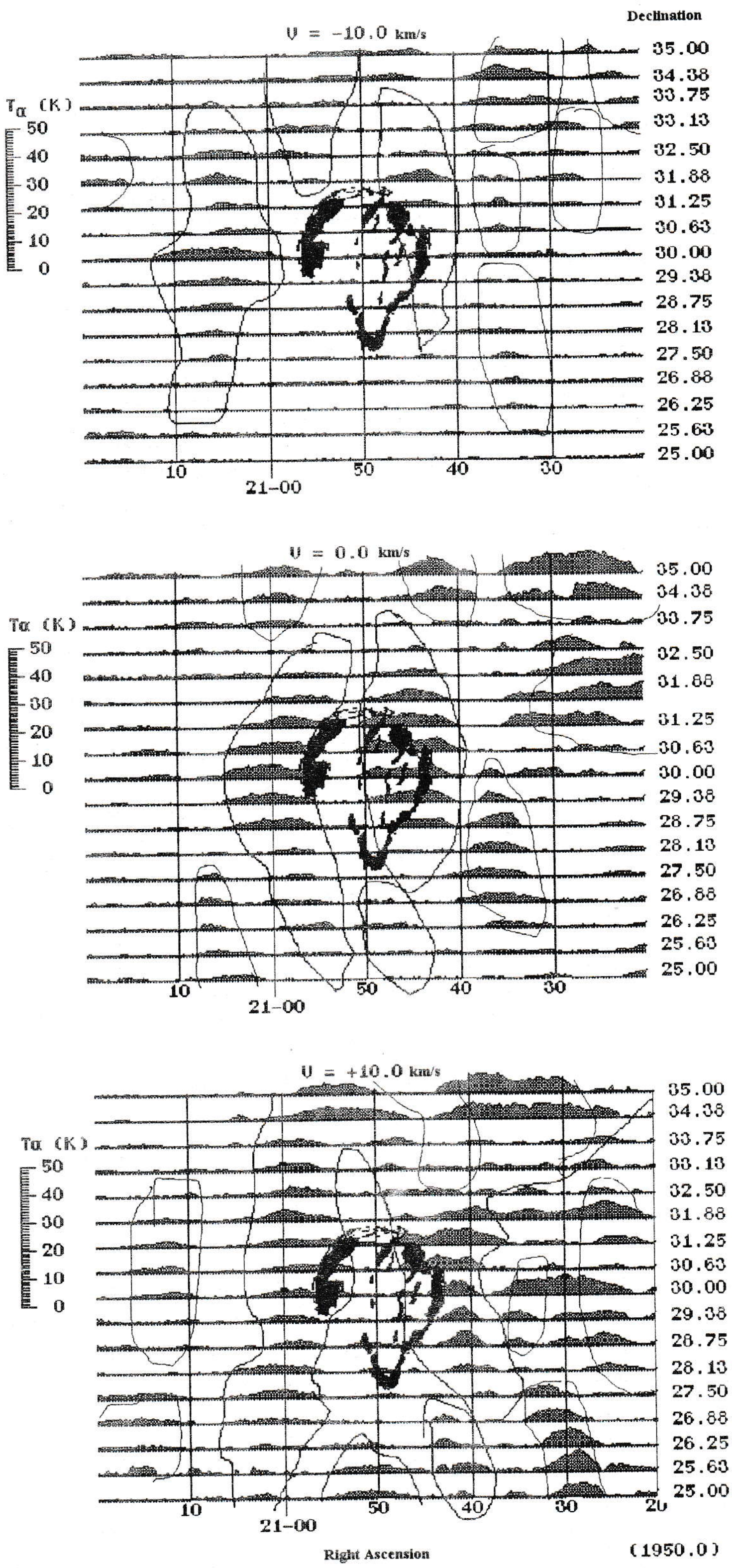

Figure 5: *Distribution of HI details in the neighbourhood of Cygnus Loop at radial velocities of about zero. Designations are the same as in Fig. 4.*

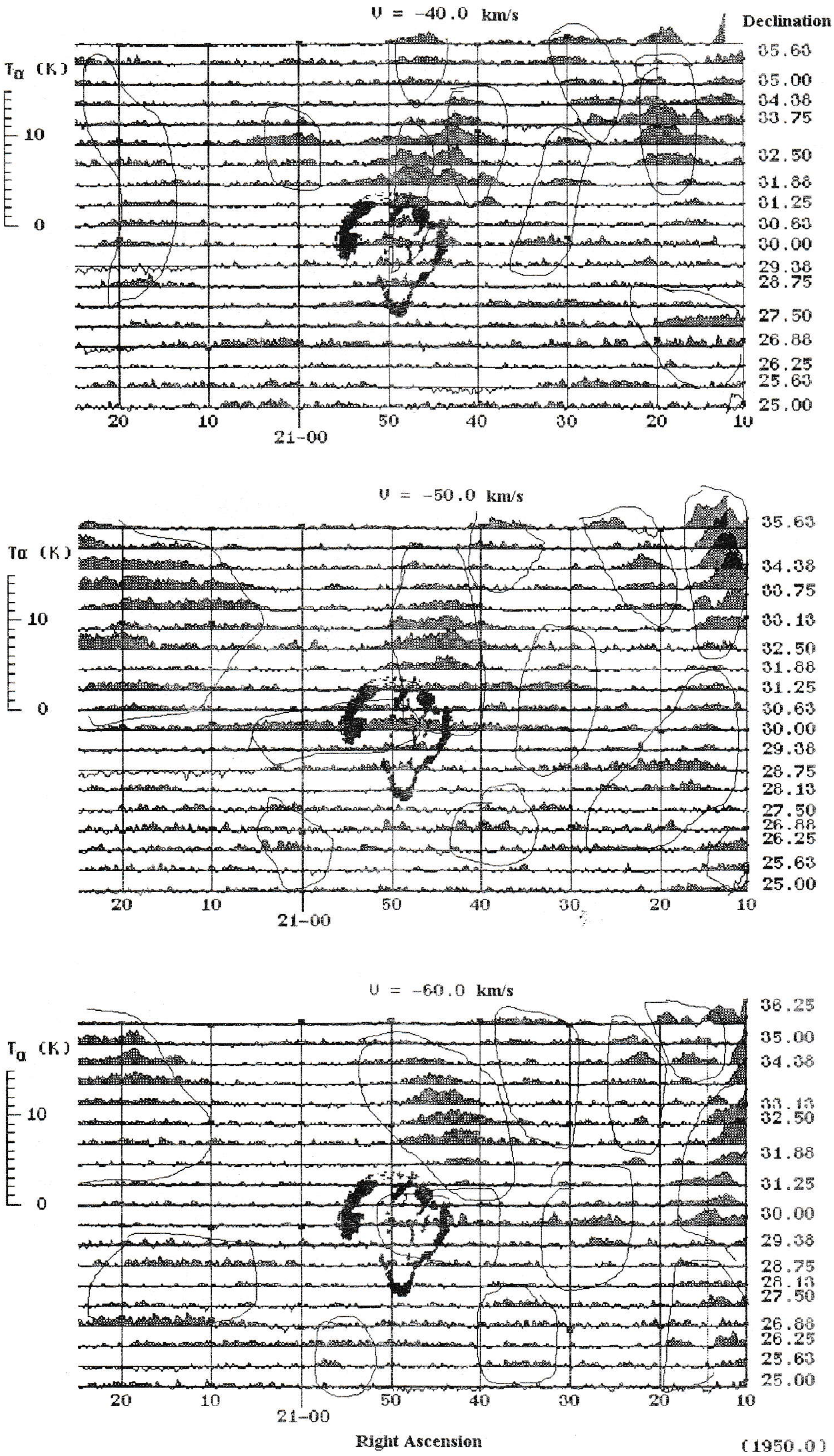

Figure 6: *Distribution of HI details in the neighbourhood of Cygnus Loop at negative radial velocities.*

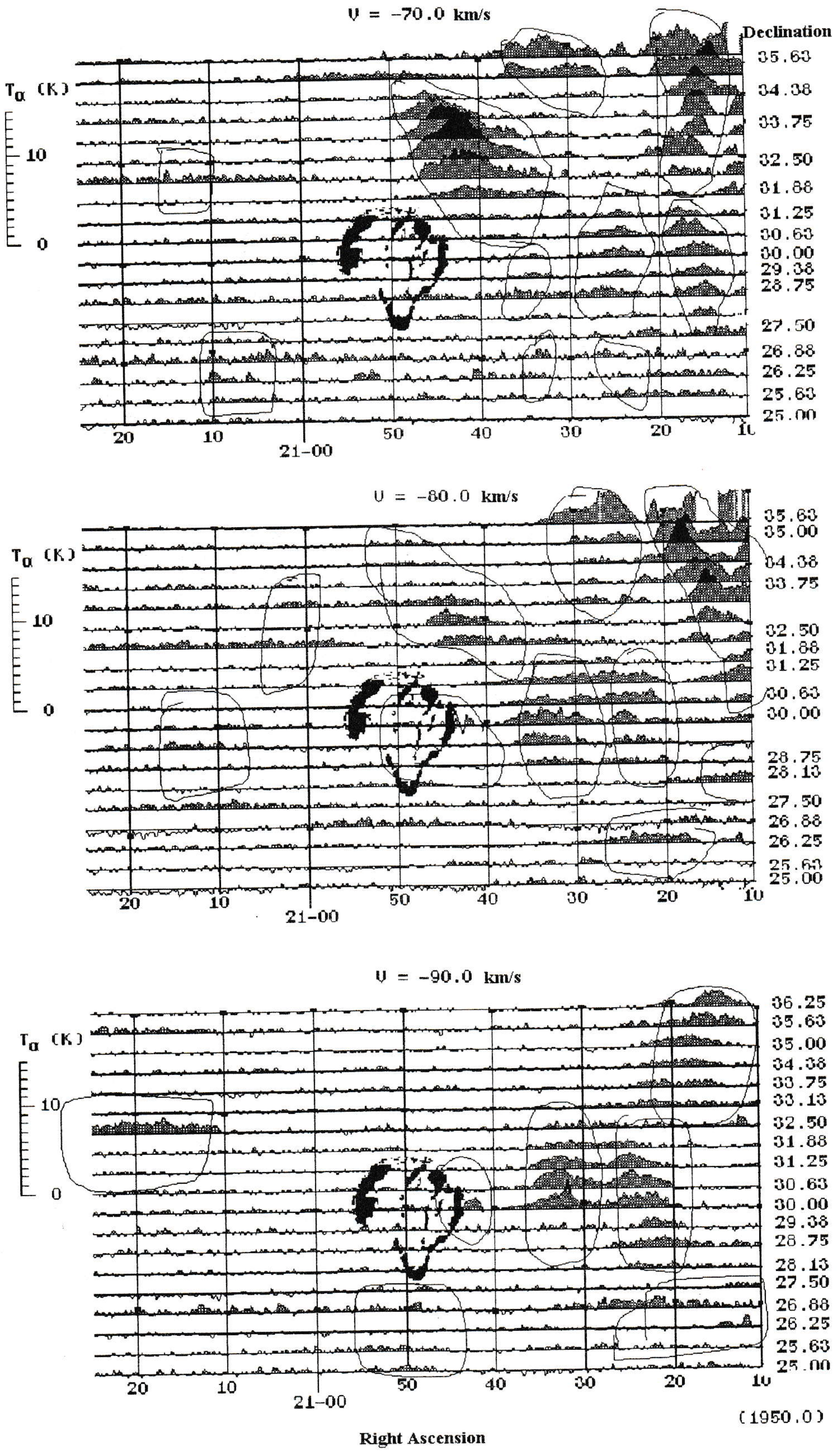

Figure 7: *The same, as in Fig. 6.*

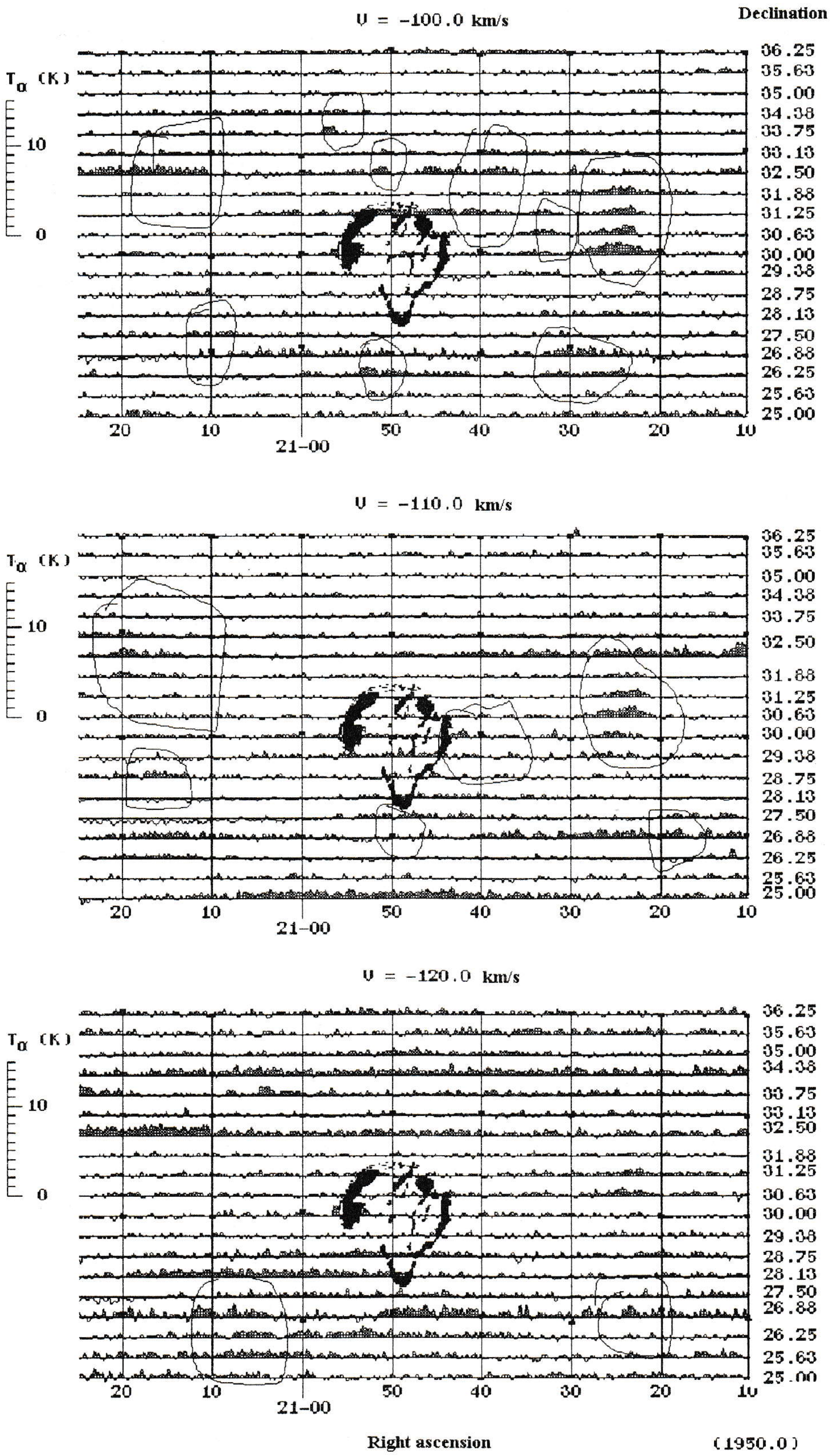

Figure 8: *The same, as in Fig. 6.*

ence of its radiation in the field of the remnant, especially in the range of radial velocities from −40 to −50 km/s. However there is no definite morphological evidence of physical connection of these clouds with the remnant, moreover practically all clouds at these velocities fall far outside the shock front of the remnant and therefore can not represent the gas, disturbed by the shock wave. Leahy and Roger (1999) have signalled about observations of the neutral hydrogen line in the field of the Cygnus Loop with an angular resolution higher than ours, about 1′. These data can refine the connection of thin HI details with fibres of the supernova remnant.

3.5. Relation between HI and dust

As it is mentioned above the distribution of IR emission in the Cygnus Loop region at four wavelengths, from 12 to 100 μm, was investigated by Arendt et al. (1992) after exclusion from IRAS data of the widespread background consisting of zodiacal light and extended Galactic emission. The authors discovered the ring-like structure of "hot" dust connected with the SNR envelope. Moreover it was divided into two parts corresponding to the regions of X–ray and optical emission. These parts of dust were investigated in detail and appropriate models were constructed.

However in a wider region of IR contours at longer wavelengths (Fig. 1c,d of this paper) some IR details were observed and associated by the authors with the well-known IR-cirruses. It can be noted that the $1 \cdot \sigma$ level of this investigation is $2.3 \times 10^{-8} W \cdot m^{-2} \cdot ster^{-1}$.

It is found, however, that the distribution of these cirruses in this region corresponds well to the HI structure at radial velocities near zero. The map of the HI details discovered in our investigation at V = +10 km/s is presented in Fig. 9 together with the outer contour of IR–emission at 100 μm from Arendt et al. (1992). This emission is located far from the SNR and is rather cold by its colour temperature. So this dust is connected with the walls of HI cavity discussed above rather than with the SNR. "Hot" dust emission is represented at the center of the picture by dashed lines. It should be noted that Arendt et al. (1992) proposed the bright IR-emission to the West and North-West of the SNR to be connected with HI clouds (DeNoyer, 1975) and CO clouds (Scoville et al., 1977). We confirm this conclusion and add such connection for the Eastern emission. It is impossible to make any quantitative estimates because of the absence of numbering on the IR-contours in the paper by Arendt et al. (1992), but it is clear that the search for the connection between HI clouds and IR-cirruses must be continued.

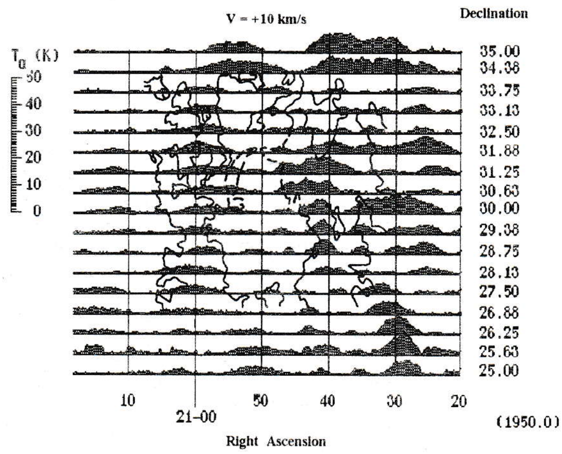

Figure 9: *HI details at V = +10 km/s. Thin lines represent outer contour of emission at* 100μm *from IRAS (Arendt et al.(1992) after exclusion of stretched background.*

4. Conclusion

The results of examination of HI distribution around the supernova remnant Cygnus Loop, obtained with a high angular resolution, have shown that the hypothesis of McCray and Snow (1979) that this supernova is located in a huge cavity of interstellar gas is quite valid. For the first time it was possible to see the complete morphology of the walls of this cavity and to show that it most likely has no relation to the stellar wind from the progenitor star. It is also worthwhile to note a surprisingly good coincidence in coordinates of the walls of the HI cavity with IR-cirruses, detected in the vicinity of the remnant by Arendt et al. (1992).

Acknowledgements. This work was done with support through grants of RFBR 96-02-165-65 and State Programme "Astronomy", project 1.3.1.2.

References

Arendt R.G., Dwek E., Leisawitz D., 1992, Astrophys. J., **400**, 562

Braun R., Strom R.G., 1986, Astron. Astrophys., **164**, 208

Dame T.M., Ungerecht H., Cohen R.S., de Geus E., Grenier I.A., May J., Murphy D.C., Nyman L.-A., Thaddeus P., 1987, Astrophys. J., **322**, 706

DeNoyer L.K., 1975, Astrophys. J., **196**, 479

Giovanelli R., Haynes M., 1979, Astrophys. J., **230**, 404

Gosachinskij I.V., Khersonskij V.K., 1987a, Astron. Zh., **64**, 1184

Gosachinskij I.V., Khersonskij V.K., 1987b, Astrofizika, **26**, 69

Gosachinskij I.V., Khersonskij V.K., 1988, Astron. Zh., **65**, 1097

Gosachinskij I.V., Losinskaja T.A., 1995, Astron. Zh., **74**, 201

Greidanus H., Strom R.G., 1992, Astron. Astrophys., **257**, 265
Hubble E.P., 1937, Carnegie Yrb, **36**, 189
Kerr F.G., Linden Bell D., 1986, Mon. Not. R. Astron. Soc., **221**, 1023
Koo B.-C., Heiles C., 1991, Astrophys. J., **382**, 204
Leahy D.A., Roger R.S., 1999, AAS Meeting 194, No. 85.04
Leahy D.A., Roger R.S., Ballantine D., 1997, Astron. J., **114**, 2081
Levenson N.A., Graham J.R., Keller L.D., Richter M.J., 1998, Astrophys. J. Suppl. Ser., **118**, 541
Levenson N.A., Graham J.R., Ashenbach B., Blair W.P., Brinkman W., Busser J.-U., Egger R., Fesen R.A., Hester J.J., Kahn S.M., Klein R.I., McKee C.F., Petre R., Pisarski R., Raymond J.C., Snowden S.L., 1997, Astrophys. J., **484**, 304
Minkowski R., 1958, Rev. Mod. Phys., **30**, 1048
McCray R., Snow T.P.Jr., 1979, Annu. Rev. Astron. Astrophys., **17**, 213
Oort J.H., 1946, Mon. Not. R. Astron. Soc., **106**, 159
Payne H.E., Bania T.M., 1979, Astron. J., **84**, 611
Scoville N.Z., Irvine W.M., Wannier P.G., Predmore C.R., 1977, Astrophys. J., **216**, 320
Tenorio-Tagle G., Rozyczka M., Yorke H.W., 1985, Astron. Astrophys., **148**, 52
Venger A.P., Gosachinskij I.V., Grachev V.G., Ryzhkov N.F., 1979, Astrofiz. Issled. (Izv. SAO), **14**, 118