

# Ionized Gas Characteristics in the Cavities of the Gas and Dust Disc of the Spiral Galaxy NGC 6946

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The parameters of the ionized gas in NGC 6946 (in the [NII]  $\lambda\lambda 6548, 6583$ ,  $H_\alpha$  and [SII]  $\lambda\lambda 6717, 6731$  lines) are investigated with the SAO RAS BTA telescope along three positions of the long slit of the SCORPIO focal reducer, passing through a number of large and small cavities of the gaseous disc of the galaxy. Most of these cavities correspond exactly to the cavities in warm dust, visible at  $5 - 8\mu\text{m}$ . We found that everywhere in the direction of NGC 6946 the lines of ionized gas are decomposed into two Gaussians, one of which shows almost constant [SII]/ $H_\alpha$  and [NII]/ $H_\alpha$  ratios, as well as an almost constant radial velocity within the measurement errors (about  $-35 \div -50$  km/s). This component is in fact the foreground radiation from the diffuse ionized gas of our Galaxy, which is not surprising, given the low ( $12^\circ$ ) latitude of NGC 6946; a similar component is also present in the emission of neutral hydrogen. The analysis of the component of ionized gas, occurring in NGC 6946, has revealed that it shows signs of shock excitation in the cavities of the gaseous disc of the galaxy. This shock excitation is as well typical for the extraplanar diffuse ionized gas (EDIG), observed in a number of spiral galaxies at their high Z-coordinates. This can most likely be explained by low density of the gas in the NGC 6946 disc (with the usual photoionization) inside the cavities, due to what we see the spectral features of the EDIG gas of NGC 6946, projected onto them. In the absence of separation of ionized gas into two components by radial velocities, there is an increasing contribution to the integral line parameters by the EDIG of our Galaxy when the gas density in NGC 6946 decreases, which explains some strange results, obtained in the previous studies. The morphology of warm dust, visible in the infrared range and HI is almost the same (except for the peripheral parts of the galaxy, where there are no sources of dust heating). The shock excitation of the ionized gas is detected also in the smallest holes, well distinguishable only in the IR images.

## I. INTRODUCTION

A close (the distance of about 6 Mpc [1, 2], so that  $1'' = 30$  pc) isolated spiral galaxy NGC 6946, visible almost face-on, stands out by its record number of both the supernovae observed there (9), and cavities (121) detected in its HI disc with sizes reaching up to 2 kpc. The largest of the known collections of HI cavities is detected through a detailed study of neutral hydrogen in this galaxy performed at the Westerbork Synthesis Radio Telescope (WSRT) [1, 2]. We shall hence use the denominations of the cavities, introduced in these papers. These data make the NGC 6946 the most suitable object for understanding the nature of the cavities. This requires detailed studies of the cavities and their environment in different regions of the spectrum, determining the parameters of the ionized gas and the characteristics of star clusters, the studies of supernova remnants, etc. An ongoing debate persists on the origin of the cavities, it is described in detail in [1, 3–5]. The hypotheses of cavity formation include: the effects of supernova explosions and stellar winds from hot stars, which in our opinion contradicts the observational data for large cavities [6]; a result of passage of a massive cloud [5] or a dark mini-

halo [7]. We will come back to this issue in the conclusion.

Our initial goal was a re-examination of cavity no.85, and the first study of a huge cavity no.107. A comparison of characteristics of gas in these two cavities is of particular interest, since these cavities extremely differ in their morphology and internal content. The first of them, including a gigantic queer stellar complex comprising a supergiant young cluster [8] was repeatedly investigated spectrally [9–11]. One supercluster seems to be enough to blow this (relatively small, with the diameter of 700 pc) hole in the gaseous disc.

However, the huge supershell no.107 reveals no objects, which could be responsible for its formation. In this paper we for the first time study the cavity spectrally. This is one of the few objects that does indeed deserve the name of the supershell, since around it a ring of high HI density and a rim of increased brightness are observed in the infrared range at wavelengths of 4.5, 5.8 and  $8.0\mu\text{m}$  (hot dust emission, associated with the dense gas and PAH molecules).

This cavity no.107 is the largest (with the diameter of 1.8 kpc) from the regular round holes in the gaseous disc of NGC 6946. From the south it is surrounded by an arc of HII regions, indicating probable star formation, which was initiated by the collision of the expanding gas shell with the surrounding gas, or triggered just when the swept up HI supershell has reached a sufficient density. The current diameter of the structure is much

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greater than the width of the gaseous disc of the galaxy, there are no sources of pressure there, and if it continues to expand, it is only due to inertia. However, the sizes of all discovered in the gaseous disc of NGC 6946 cavities clearly exceed its effective depth. This is a general rule for other spiral galaxies, and remains a difficult problem for the hypotheses, explaining the formation and swelling of shells by any central pressure source possible [2]. The gas breakthrough beyond the boundaries of galactic disc from the expanding shell (observed at least twice in our Galaxy, (see, e.g., [12]), should obviously lead to a halt in the expansion of the cavity in the galactic disc. In several cases the signs of this halt (the gas fountains), are apparently observed in NGC 6946 (see [1, 2]).

In addition to the above-mentioned cavities no. 85 and 107, each of the three slit positions passes through a number of other cavities. The objective was to study the variations of radial velocity and excitation parameters of the ionized gas along the slit in hope of getting the data to explain the origin of cavities in the gas and dust disc of NGC 6946 and other galaxies.

We immediately note that the morphology of warm dust, illustrated by the image obtained in the far IR range ( $5 - 8\mu\text{m}$ ) by the Spitzer Space Telescope, reveals an almost exact conformity with the picture, revealed in neutral hydrogen, which is correct both for the cavities and for the regions with high density of gas and dust. Moreover, a high resolution of the infrared image (compared with the pattern in neutral hydrogen) allows to discern small holes in the interstellar medium, practically not detected at the wavelength of 21 cm.

## II. OBSERVATIONS

The observations were carried out by Afanasiev on August 16–17, 2007 at the 6-meter BTA telescope of the Special Astrophysical Observatory of Russian Academy of Sciences (SAO RAS). We used the SCORPIO focal reducer (see its description in [13]) and a long ( $6'06''$ ) slit, the scale along which amounts to  $1\text{px} = 0''.357$ .

Table. I lists position angles and the cavities numbers located near the centers of the slits.

Figure 1 shows the positions of the spectrograph slits with respect to the HI cavities. The numbers of cavities from [1, 2] are marked, as well as the cavities, usually coinciding with them, but smaller in size, recently discovered by Bagetakos et al. [3]. The slit width amounted to  $1''$ , the spectral resolution  $FWHM$  of about  $3.4\text{ \AA}$ . The accuracy of the wavelength scale along the lines of the night sky is  $20 - 30\text{ km/s}$  for the lines, obtained with the S/N ratio of about 5 or higher (as can be clearly seen from the error bars in the figures, where the distribution of radial velocities along the slit is given).

The spectrum of the night sky (at the coordinates  $\text{RA} = 00^{\text{h}}10^{\text{m}}00^{\text{s}}.00$  and  $\text{DEC} = +18^{\circ}00'00''.0$ ; the galactic latitude of about  $-42^{\circ}$  and the distance from the

NGC 6946 of about  $50^{\circ}$ ) was observed immediately after NGC 6946 under the same conditions as the galaxy itself. The spectra obtained were used to subtract the night sky from the spectrograms of the object. The choice of the position angle of about  $-33^{\circ}$  was made hoping that at this angle (parallel to the minor axis of the galaxy) the effect of its rotation on radial velocity is minimal, and local features of radial velocities should be visible.

## III. DETECTION OF TWO COMPONENTS IN THE LINE PROFILES OF IONIZED GAS

In the process of observations Afanasiev and Silchenko noticed that the doublet of forbidden lines of sulfur (they are free from the sky emission) is observed not only throughout the galaxy, but also very far beyond its visible boundaries in the spectrograms obtained higher by declination  $2^{\circ}$  from NGC 6946.

It prompted an idea that these lines may belong to the foreground, our Galaxy, which is quite possible, given the relatively low ( $11^{\circ}.7$ ) latitude of NGC 6946. Therefore, as shown in Fig. 2, we performed a Gaussian decomposition of the radial-velocity profiles of the  $\text{H}\alpha$ , [NII] and [SII] lines into two components (bearing in mind that the last two lines are doublets).

It turned out that along the entire slit there is a component that has a virtually constant radial velocity over the entire length of the spectrum (usually in the range of  $-40 \pm 7\text{ km/s}$ ) and a constant within the errors flux ratio in the lines of  $\text{H}\alpha$ /[NII] and  $\text{H}\alpha$ /[SII]6717 (Fig. 3). The velocity obtained from the second component varies along the spectrum and is closely correlated with the details of morphology of the gas distribution in NGC 6946. It follows that the first component originates in the diffuse ionized gas of our Galaxy, while the second component comes from the NGC 6946. This can be seen directly in the spectra (including the lines of the night sky), which show the regions including the [NII] doublet,  $\text{H}\alpha$  and the [SII] doublet in all the three slits (Figs. 4–6).

These images show the same smooth and sharp boundary in the lowest velocities, especially in the sulfur lines, clean of the night-sky lines. This boundary is defined by the emission coming from our Galaxy. It represents the velocity of extraplanar diffuse ionized gas (EDIG) of the Milky Way in the direction of NGC 6946. The upper boundary is outlined by the ionized gas of NGC 6946 itself, with its sharply inhomogeneous intensity and variable radial velocities.

The presence of a very substantial admixture of the foreground ionized gas emission has strangely never been detected in the previous studies (including ours), and its indirect signs (described, for example, in [14] as far back as in 1988) were attributed to a poor accounting of the background sky, or else the peculiar radial velocities in several regions of NGC 6946. The flux from the ionized gas of the foreground is demonstrated in Figs. 4–9 by the dashed line, outside the HII regions it usually exceeds the

TABLE I: Log of observations

Date	Hole	Position angle, deg.	Spectral range, Å	Dispersion, Å	T <sub>exp</sub> , s	Seeing
16/17.08.2007	107	−33(147)	6100–7100	0.52	1800	2''
16/17.08.2007	107	180(0)	6100–7100	0.52	1800	2
16/17.08.2007	85	−34(146)	6100–7100	0.52	1200	1.5

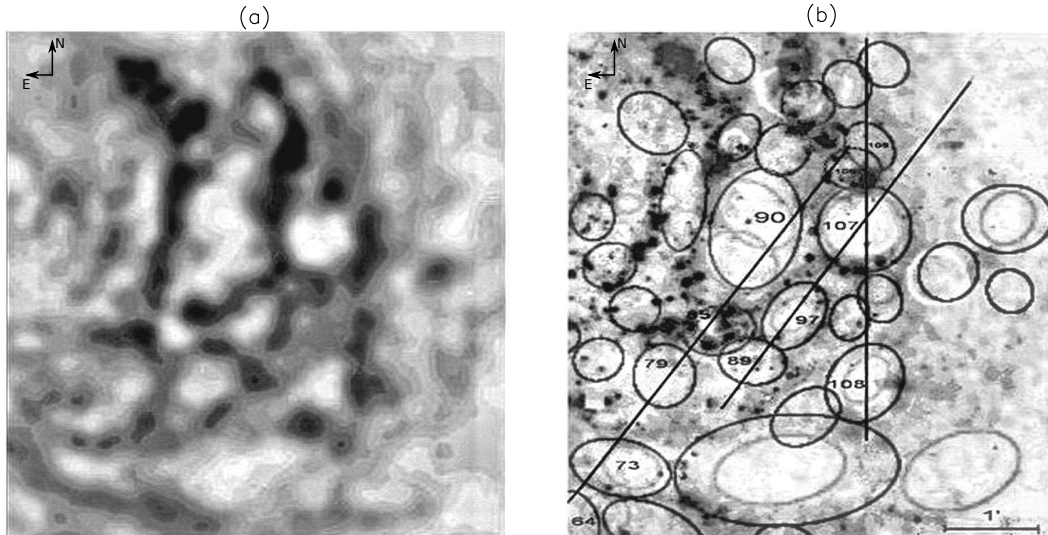


FIG. 1: The Western region of the NGC 6946 galaxy in the line of neutral hydrogen. (a) the image in the HI line according to [1]; (b) the image in the line of HI (in gray, based on the data from [3]) and the HII region (in black). We marked the positions of cavities (according to [1–3]), their numbers according to [1, 2] and the positions of our slits. The gray and white outlines of the cavities are given based on [3].

flux from NGC 6946. Note that Fig. 2 was built exactly from the spectral regions of NGC 6946, corresponding to the HII regions.

#### IV. RADIAL VELOCITIES

The properties of the foreground gas will be discussed below, for now we will discuss exclusively the NGC 6946. Figures 7, 8 and 9 demonstrate the radial velocities in three lines of ionized gas both for NGC 6946 and for the foreground for the three slit positions, as well as the radial velocity in HI along all the slit positions, that were kindly provided by R. Boomsma (for details of his observations, see [1]).

The averaging was carried out in the regions sized  $2.8''$ . First of all, note that the velocity dispersion (or rather, the scatter of measurements from point to point) sharply increases in the cavities. This may be a sign of their expansion, but, more probably, a consequence of the lower signal-to-noise ratio for the gas flux of lower density in the cavities.

Sometimes a comparison of radial velocities of different species of ionized gas reveals intriguing differences. In the cavities no. 90 and 73 the radial velocities in  $H_\alpha$  drastically deviate from the mean towards the negative

velocities, whereas the [SII] and [NII] lines give an almost constant velocity. Moreover, the lines of sulfur reveal a deviation towards the positive velocities in the cavity no. 90 (Fig. 7). In this cavity neutral hydrogen splits into two components based on velocity, one of which continues to smoothly move along the slit, while the other indicates that one of the walls of the cavity is approaching us, deviating in the same direction as the  $H_\alpha$  velocities, while ionized hydrogen shows an even greater velocity of this wall. Perhaps, this points to the outflow of gas from the shell.

The expansion of the much thicker than the HI disc of the galaxy cavity seems inexplicable, as already noted (see also [2]). It is possible that in the case of cavity no. 90 we are dealing not with an expanding cavity in the gaseous disc, but simply with an unusually sharply limited interarm region of low density (as already suspected in [1]). However, the cavity no. 90 is shown in [3] to be double, what can be seen in Fig. 1. The diversity in the behavior of radial velocities of different species of ionized gas inside this super-giant cavity (Fig. 7, the interval along the slit is  $80''$ – $140''$ ) can not be unambiguously explained.

Note also the curious “peaks” (the deviations towards higher velocities) observed in the cavities no. 90 and no. 107 solely in the lines of [SII] and [NII], respectively

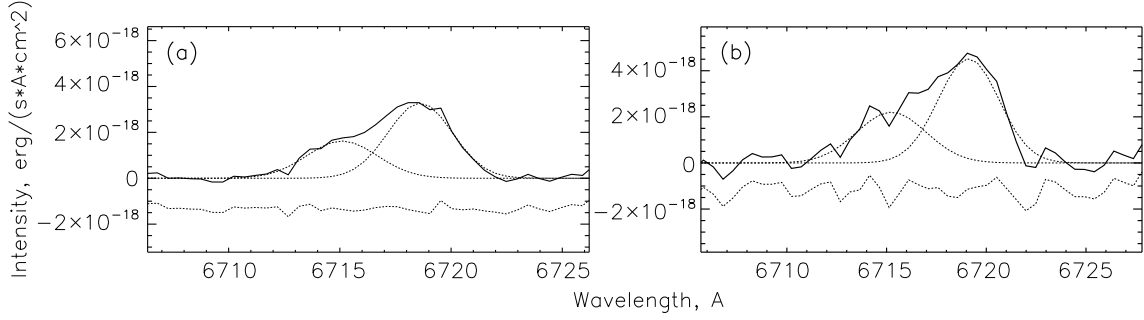


FIG. 2: An example of decomposition of the line profiles of sulfur [SII]  $\lambda 6717$  into two components. The observed profile is shown by the solid line, the decomposition into 2 Gaussians and the remainder of their subtraction—by the dashed line. The right component in the decomposition corresponds to NGC 6946, the left component—to our Galaxy. The remainder of subtraction of the Gaussians from the observed spectrum is shifted down for clarity, the median value of the remainder is zero.

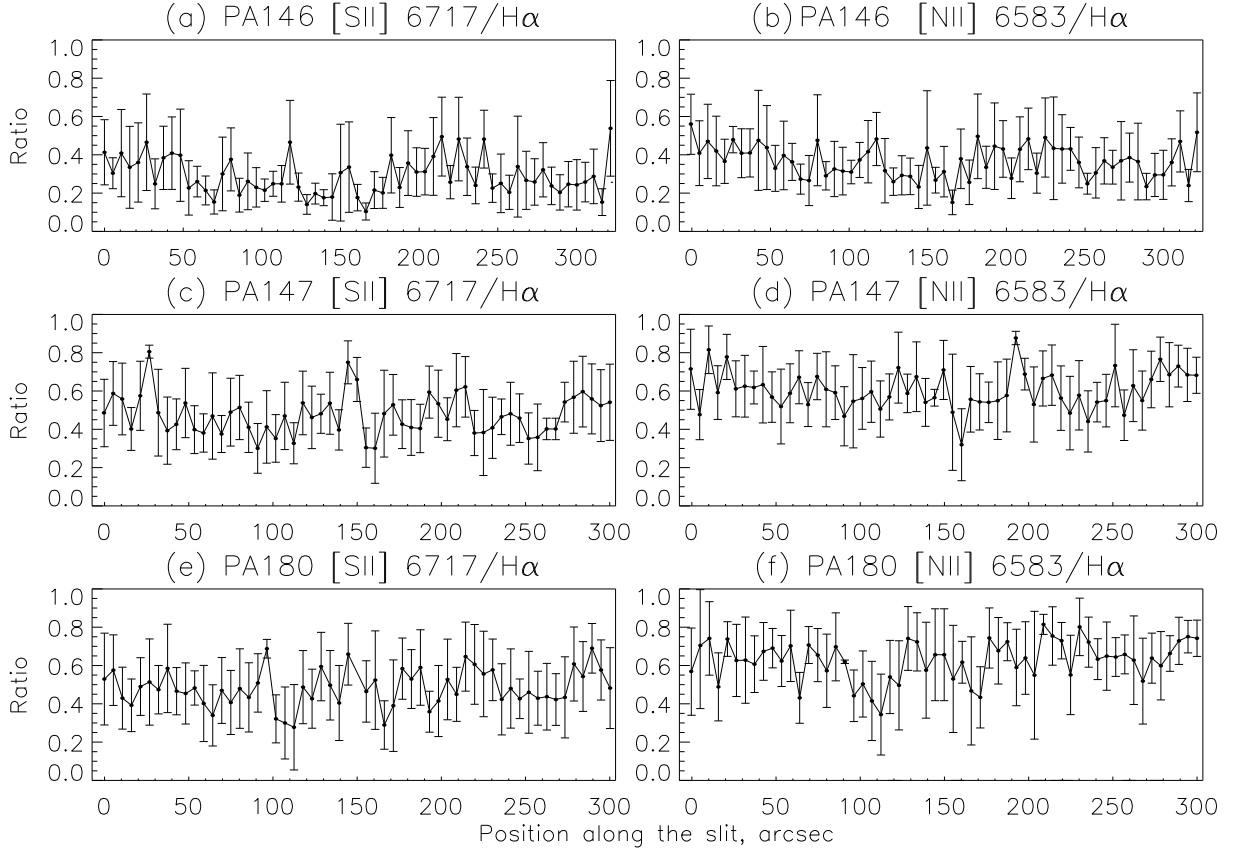


FIG. 3: The flux ratio (along all three slits) in the lines of [SII]  $\lambda 6717$  and [NII]  $\lambda 6583$  to the  $H\alpha$  line flux in the component of ionized gas, the radial velocity of which points to the belonging to our Galaxy. The similarity of line profiles along the slit (especially noticeable with the slit position PA 147) confirms their origin in the same discrete warm ionized medium (WIM) clouds of our Galaxy.

(Figs. 7 and 8). Note also that the lines of [SII] of the foreground give the velocity peak in the positive direction in the region of high-density of ionized gas in NGC 6946. This can be explained either by accident, or by a not quite accurate for such densities separation of spectral lines into the components coming from NGC 6946 and the foreground.

Particularly note in Fig. 7 a narrow dip in the velocity

along the  $H\alpha$  line, corresponding to a small region of lowest gas density and the lowest radial velocity inside the hole no. 85, the center of which is located  $7''$  to the east of the supercluster. This region was found in [9] and called a deep dip in [10]. A hint at this dip can also be found in the [SII] line (but not in the [NII] line) in Fig. 7.

Even inside the largest cavities (nos. 90 and 107) we do not observe any features in the radial velocity field

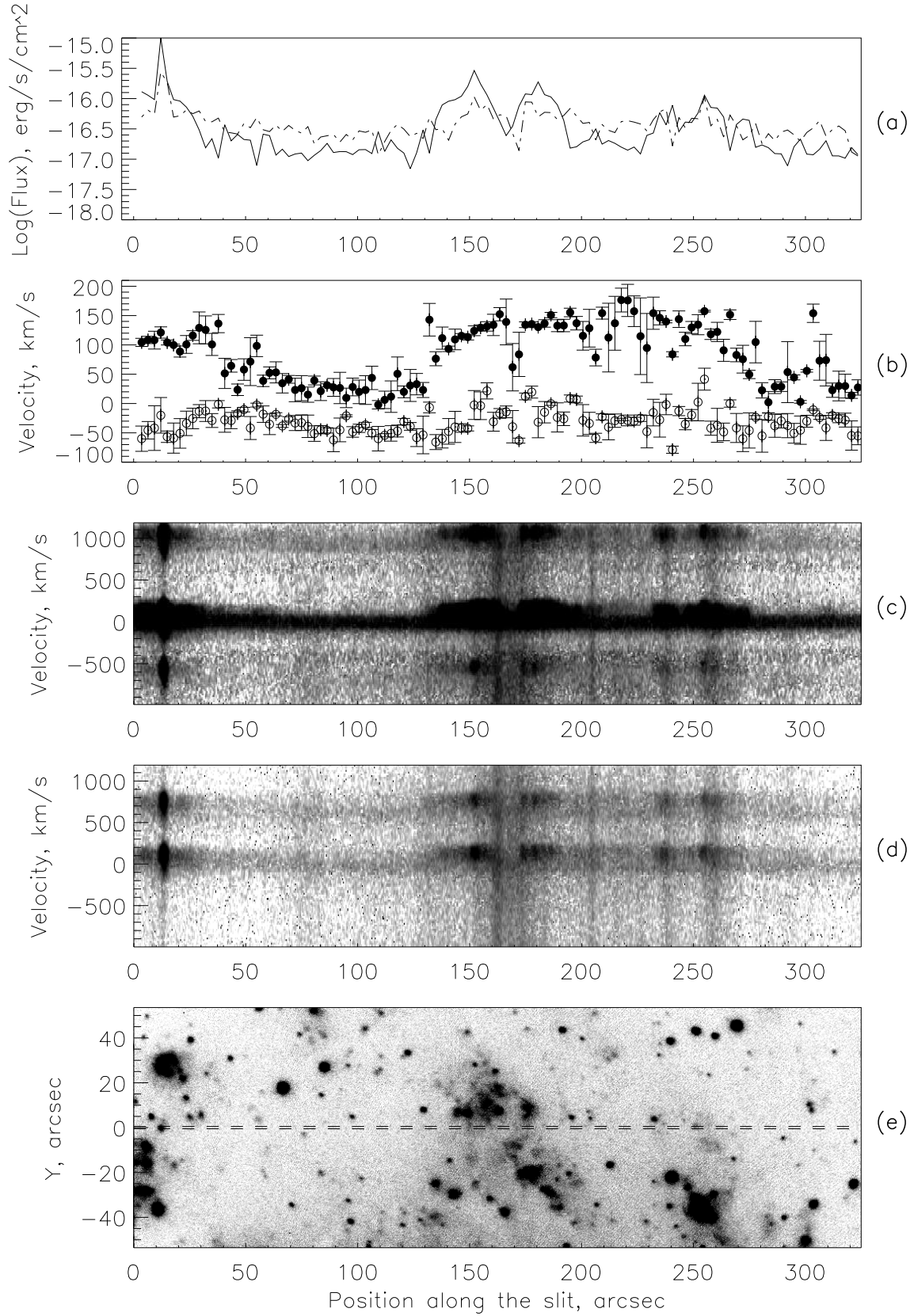


FIG. 4: The variations of spectral characteristics along the slit position PA 146, passing through the cavity no.85: (a) the fluxes in  $\text{H}_\alpha$  from NGC 6946 (the solid line) and the WIM of our Galaxy (the dashed-dotted line); (b) radial velocities of ionized gas of NGC 6946 (the upper curve) and the WIM of the Galaxy (the bottom curve) in the  $\text{H}_\alpha$  line; (c) a part of the spectrum in the region of the  $\text{H}_\alpha$  line. The wavelength scale is transformed into the velocity scale relative to the  $\text{H}_\alpha$   $\lambda 6562.8$  line; (d) similar to the plot (c) for the [SII] lines. The wavelength scale is given relative to the [SII]  $\lambda 6717$ ; (e) the slit position in the  $\text{H}_\alpha$  image of the galaxy.

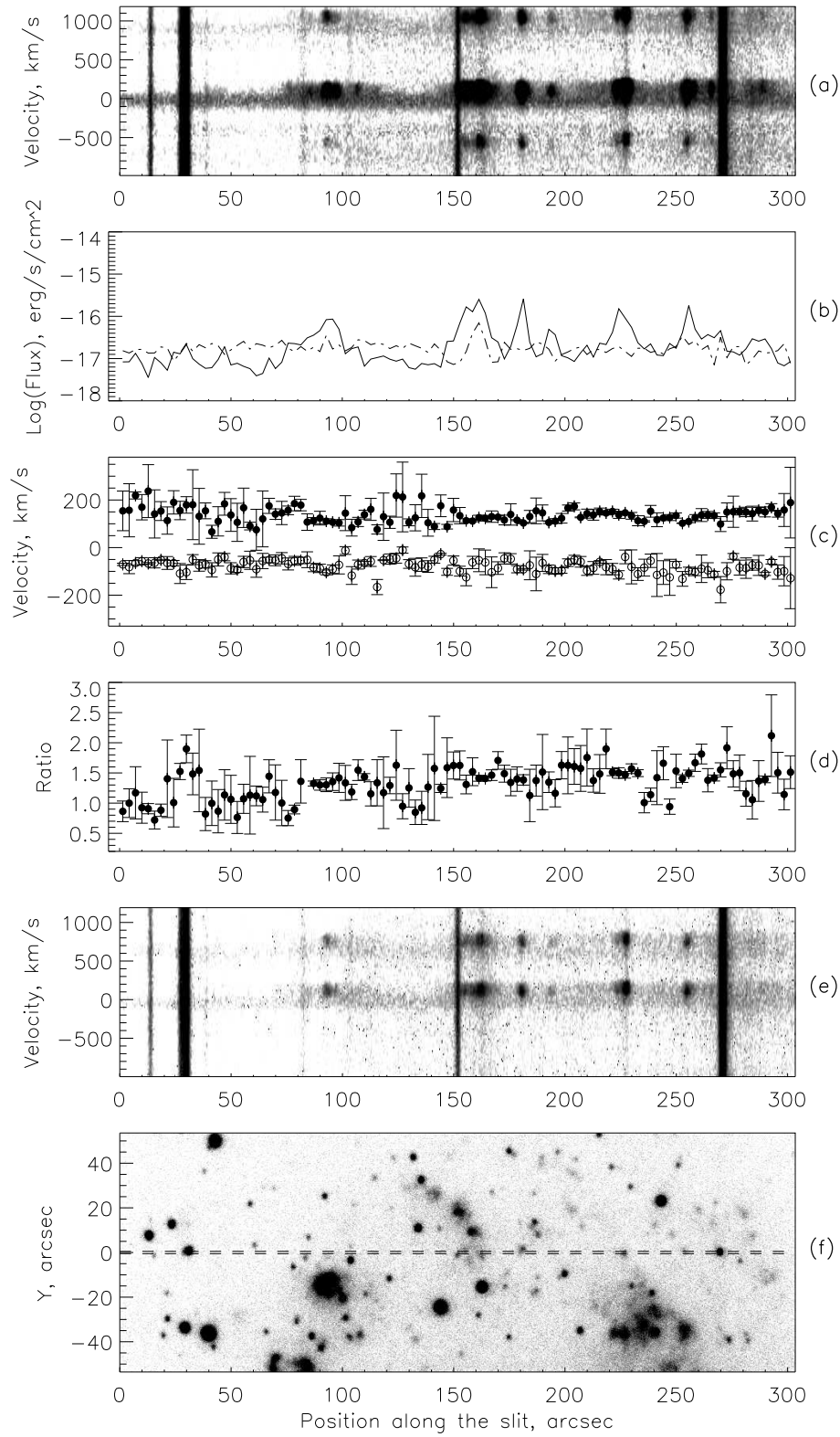


FIG. 5: The variations of spectral characteristics along the slit position PA 147, passing through the cavity no. 107: (a) a part of the spectrum in the region of the  $H_\alpha$  line. The wavelength scale is converted into the velocity scale relative to the  $H_\alpha \lambda 6562.8$  line; (b) the fluxes in the  $H_\alpha$  line from NGC 6946 (the solid line) and the WIM of our Galaxy (the dash-dotted line); (c) radial velocities of ionized gas of NGC 6946 (the upper curve) and the WIM of our Galaxy (the bottom line) in the  $[SII] \lambda 6717$  line; (d) the flux ratio in components of the doublet line  $[SII] F(\lambda 6717)/F(\lambda 6731)$ ; (e) similar to the plot (a) for the  $[SII]$  lines. The wavelength scale is given relative to the  $[SII] \lambda 6717$  line. (f) the slit position in the  $H_\alpha$ -image of the galaxy.

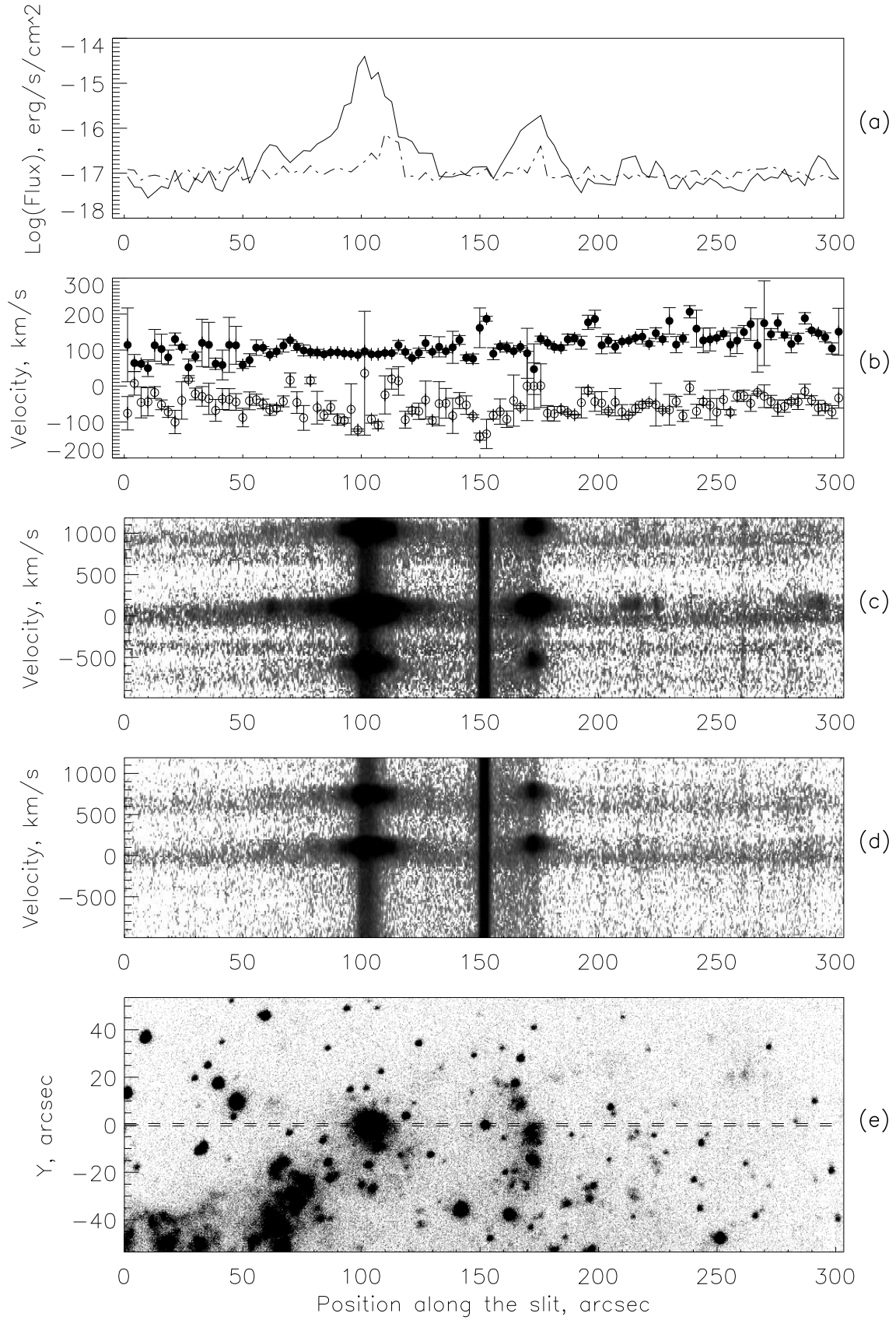


FIG. 6: The variations of spectral characteristics along the slit position PA 180, passing through the cavity no. 107. The plots (a)–(e) are similar to those shown in Fig. 4.

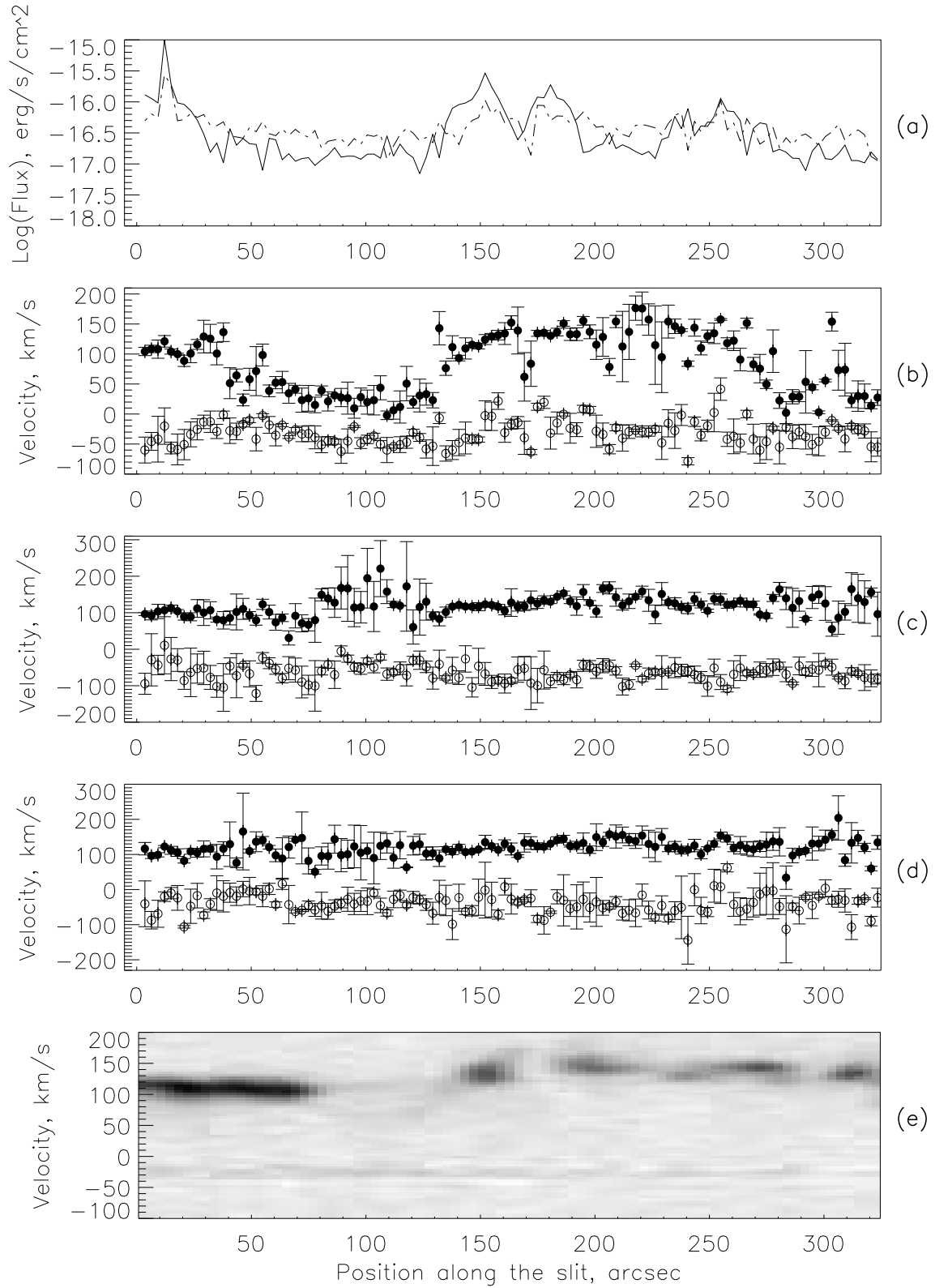


FIG. 7: The variations of spectral characteristics along the slit position PA 146, passing through the cavity no. 85: (a) the  $H_{\alpha}$  line fluxes from NGC 6946 (the solid line) and the WIM of our Galaxy (the dashed-dotted line); (b) radial velocities of ionized gas in NGC 6946 (the upper curve) and in the WIM of our Galaxy (the bottom curve) in  $H_{\alpha}$ ; (c) the same, in the  $[SII] \lambda 6717$  line; (d) the same, in the  $[NII] \lambda 6583$  line; (e) radial velocities in the HI 21 cm line.



of ionized gas, similar for all the lines. Therefore, the hopes of finding the expansion of the cavities have been unfulfilled. The behavior of radial velocities of neutral hydrogen within the cavities is also ambiguous; it was discussed by Boomsma [1].

## V. LINE FLUX RATIOS

We found that within the cavities the flux ratios  $[\text{SII}]/\text{H}\alpha$  are systematically higher than beyond their limits, whereas for the HII regions, including those located at the periphery of the cavity no. 107, the flux ratios correspond to those, normal for the photoionization of gas by hot stars.

A supergiant complex of HII regions is located at the northern edge of the second in size and brightness in NGC 6946 supershell no. 107. This complex is situated at the junction of cavities no. 107 and 106 (Figs. 1 and 10), and could be regarded as an illustration of the possibility of formation of giant star-forming regions via collisions of two expanding shells of gas.

The hypothesis of star formation, induced by the shock wave collision, was proposed by Chernin et al. [15] and then repeatedly supported by other authors. This HII complex, located next to the HII cavity no. 107 is crossed by our slit position PA 180. Its spectrum did not reveal any signs of shock excitation, despite our expectations, on the contrary, the ratios of both  $[\text{SII}]6717+6731$  and  $[\text{NII}]6583$  to  $\text{H}\alpha$  are minimal here (Fig. 10).

It is considered (see, e.g. Moiseev et al. [16]) that the value of flux ratio in these lines in excess of 0.4 indicates that the main contribution into the gas ionization is made by the shock waves. In Fig. 11 we drew vertical lines through the points of maximum values of the  $[\text{SII}]/\text{H}\alpha$  ratio, and a horizontal line through the value of this ratio equal to 0.4. We can see that the slit positions where it exceeds 0.4 correspond to the HI cavities, more accurately—to the boundaries of the cavities, outlined by warm dust. Two narrow peaks of the  $[\text{SII}]/\text{H}\alpha$  ratio (at the coordinates along the slit of  $170''$  and  $240''$  on both sides of the cavity no. 97) accurately correspond to the positions on the slit occupied by two mini-cavities in warm dust, almost indistinguishable in the HI images.

## VI. DISCUSSION

### A. Extraplanar Diffuse Ionized Gas

The increased ratio of the flux in the forbidden lines of nitrogen and sulfur to the flux in  $\text{H}\alpha$  that we found in the cavities of NGC 6946 are well known in the extraplanar diffuse ionized gas (EDIG), found outside of the planes of galaxies, visible edge-on, as well as in the EDIG of our Galaxy. Our data (Figs. 3 and 7–9) show that the entire region of NGC 6946 reveals gas with a nearly constant velocity of about  $-40$  km/s, which is certainly the diffuse

ionized gas (EDIG) of our Galaxy, located outside its plane.

The intensity ratios of the gas along our slits are demonstrated in Fig. 3. For the slit, passing through the cavity no. 85, these ratios point rather to the photoionization, and for both slits passing through the cavity no. 107, and especially in the slit position PA 147, they are typical for shock excitation. It can be assumed that these differences reflect the angular sizes of the DIG/WIM clouds of the Galaxy, and the differences in the ionization parameters of various clouds.

Note that over the entire length of each slit the ratios of these lines vary almost chaotically, more precisely, they are constant within the errors. This bears no resemblance with the intensity ratio variations of the component coming from the gas of NGC 6946, which are closely linked with the morphology of the gas and dust disc of the galaxy.

Note that some figures in Boomsma's thesis [1], for example, on p. 68 and 69, reveal elongated HI clouds of the foreground with sizes of the order of ten minutes and velocities ranging from  $-67$  to  $-8$  km/s. The clouds with similar characteristics can be as well discerned in the lane of constant velocity, present in the figure demonstrating the rotation curve of NGC 6946 in Boomsma et al. [2], which the authors do not even mention. This HI lane with the radial velocity of about  $-35 \pm 5$  km/s exactly corresponds to the radial velocity component we have found from the lines of ionized gas; it extends along the entire length ( $26'$ ) of the rotation curve of NGC 6946, built along the major axis of the galaxy in this paper, but the authors [2] do not comment on its presence. We may suspect that the high-latitude neutral gas of our Galaxy in the direction of NGC 6946 is concentrated in a layer of clouds closely adjacent to each other with a small velocity dispersion. Based on the figures from [1] we can estimate the angular sizes of some of these clouds. They are close to the characteristic sizes of not completely random (but small, Figs. 7–9) radial velocity variations of the ionized gas of the foreground on our spectrograms. This probably indicates that the neutral and ionized gas of the Galaxy at high latitudes is concentrated in the same clouds, and then we can not consider it quite so diffuse.

The gas velocity of the foreground we found in a projection to NGC 6946 is within the velocity of the EDIG of the Galaxy, observed in this region by Haffner et al. [17]. This team and some other authors demonstrate that this gas of the Galaxy is characterized by high values of the  $[\text{NII}]/\text{H}\alpha$  and  $[\text{SII}]/\text{H}\alpha$  line intensity ratios, similar to those observed in the diffuse ionized gas at high (about 1–2 kpc) Z-coordinates in the galaxies, seen edge-on. This way, it was found in [18] that the  $[\text{SII}]/\text{H}\alpha$  ratio in NGC 4302 increases from 0.2 at  $Z = 0$  kpc to 0.6 at  $Z = 1 - 2$  kpc.

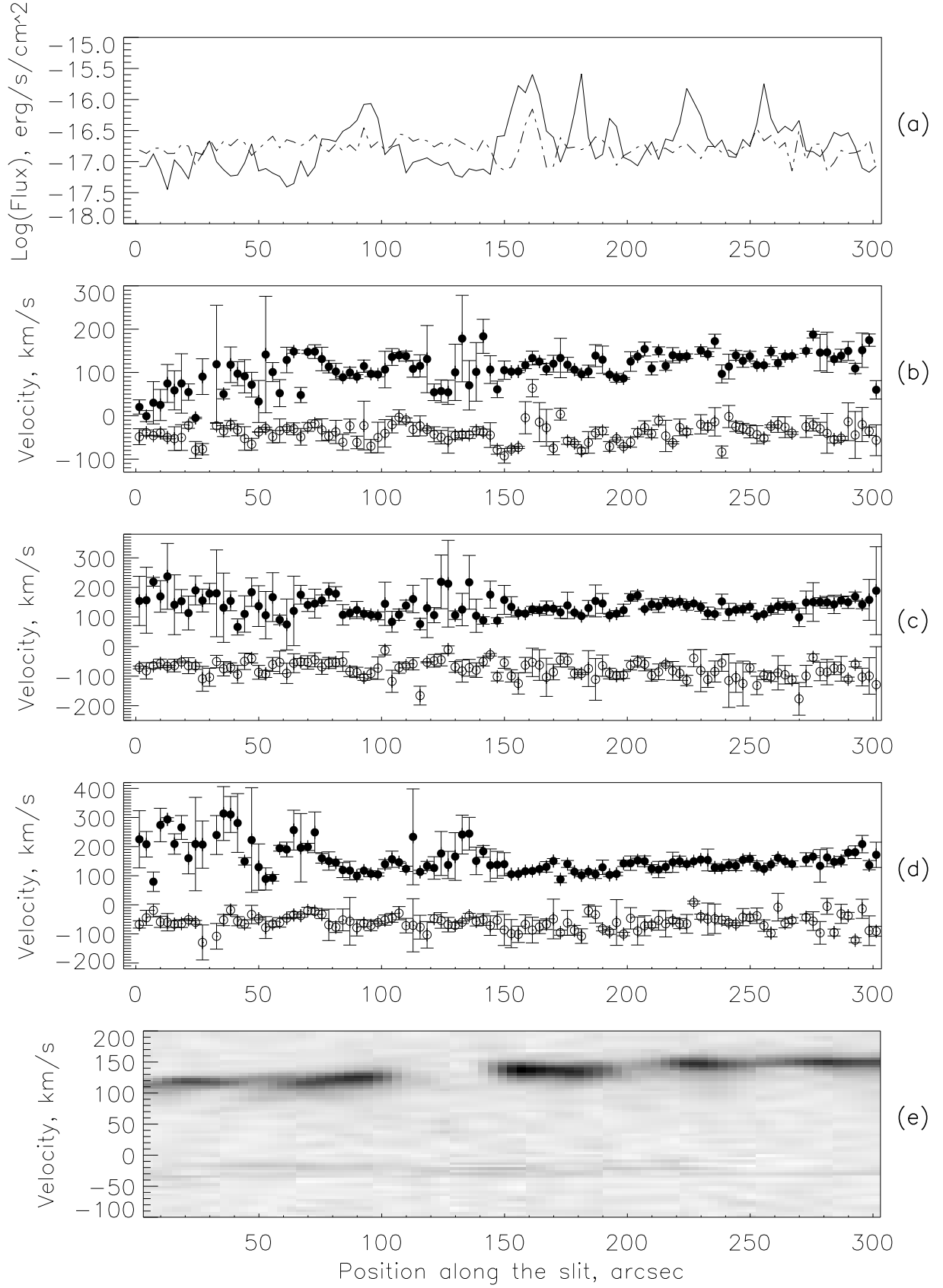


FIG. 8: The variations of spectral characteristics along the slit PA 147, passing through the cavity no.107. The plots (a)–(e) are similar to those shown in Fig. 7.

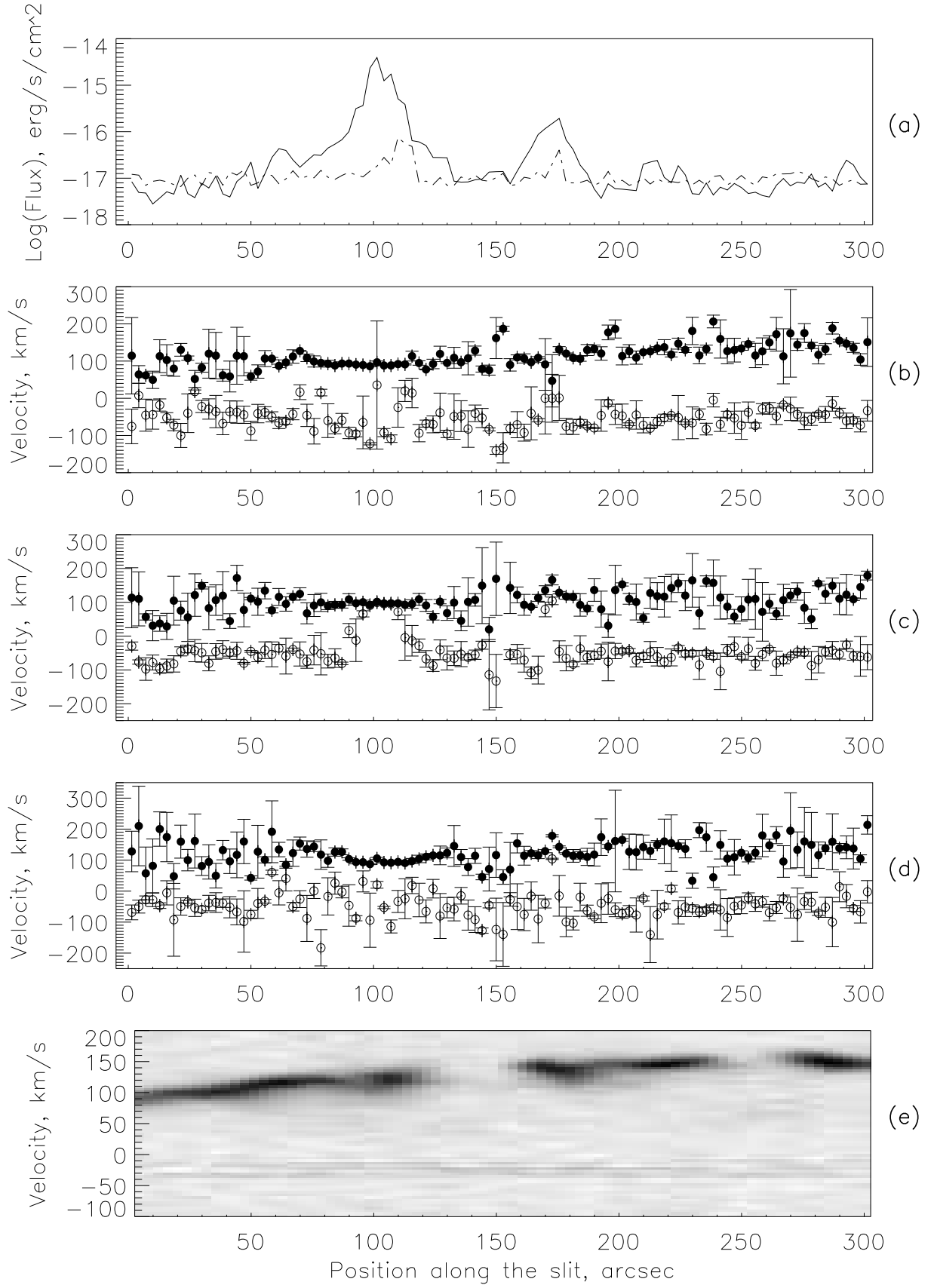


FIG. 9: The variations of spectral characteristics along the slit PA 180, passing through the cavity no. 107. The plots (a)–(e) are similar to those shown in Fig. 7.

## B. The Origin of Cavities in the Disc of NGC 6946

Thus, HII regions, located directly at the boundaries of HI cavities in NGC 6946 show the usual line ratio, typical of ionization by hot stars. However, the formation of regions, embordering the cavities, and, above all, the HII regions and stars, forming an arc along the southern boundary of the giant (with the diameter of 1.8 kpc) cavity no. 107 is almost evidently related to the sweep-up of the gas by the expanding shell of the cavity. The absence of spectral features of the shock wave in these HII regions means that the expansion has stopped (or its rate has become slower than the velocity dispersion in the surrounding gaseous disc). The line flux ratio is probably coming back to that, typical of photoionization within the time scale, shorter than the lifetime of O-type stars (i.e. less than about 2 Myr). As mentioned above, there are no indisputable signs of the expansion of cavities/shells in the radial velocities along the cavities and their boundaries neither.

The halt in the cavity expansion is not surprising if it was caused by pressure from within, since the sizes of almost all cavities are undoubtedly larger than the (effective) thickness of the gaseous disc of spiral galaxies (in NGC 6946 in particular). They are hence open to the issue of compressed gas. One way or another, the cavity no. 107, exceptional in its size and regular round shape, reveals no signs of star clusters, which could be a source of cavity expansion. Some deviations of radial velocities inside the hole no. 107 (from the values outside of it) can be seen in Fig. 9, but they are oppositely directed for different gas species, and therefore might hardly be identified as galactic fountains (gas outflows from the hole).

As emphasized by Boomsma et al. [2] and many other authors, it is unclear how the giant sizes of cavities can be reconciled with the popular hypothesis about the origin of the cavities under the influence of a pressure source located inside of them (from supernovae and/or the stellar wind of O-type stars). The cavities with effective sizes exceeding the thickness of the gaseous disc are known in our Galaxy as well. This way, the height of the gas filaments, limiting by the Z-coordinate the gas, flowing from the HI supershell in GSH 242-03+37, one of the largest in our Galaxy (its radius is around 560 pc) is about 1.6 kpc above and below the galactic plane [12]. Note, however, that the thickness of the gaseous disc in irregular galaxies is much larger than that in spirals, which probably explains the expansion of gas shells often observed in them (e.g., in IC 1613, see [19]).

Our Figs. 10 and 11 show that the line intensity ratios inside the cavities correspond to the shock excitation. The question arises whether we see the gas in NGC 6946 projected on the cavity at large Z-coordinates, where it has typical for the EDIG line ratios, similar to those observed at the shock excitation, or whether the gas of the galactic disc was excited in the cavities at their formation.

The first hypothesis seems more probable. Inside the

cavities of the gas and dust disc in NGC 6946 the density of gas (and ionized gas too) is sharply reduced, and at large Z-coordinates it is obviously equal both over the cavities and beyond. As follows from Fig. 11, the ratio  $[SII]/H_\alpha$  anticorrelates with the flux in the  $H_\alpha$  line, the value of which indicates that inside the cavities, the contribution of the disc gas (with “normal” photoionization by hot stars) in the integral gas characteristics along the line of sight is several times smaller. At larger Z-coordinates in NGC 6946, just like in our and other galaxies, we should as well find the EDIG with the ionization parameters close to those, typical of shock excitation. In the projection on the disc cavities, the contribution of the EDIG at high Z-coordinates dominates over a small contribution in the cavities of the gaseous disc. This is why we observe in the cavities (according to our hypothesis, above them) the ionization parameters, corresponding to the shock excitation. This hypothesis is also supported by the argument that the ionization of such nature is preserved in all holes, including the smallest. Note that there is no correlation between the value of this ratio and the cavity size. This can be viewed as an indication that the anomalous ionization in the region of cavities is not physically related with them. Apparently, owing to the large amount of cavities in the disc of NGC 6946, we can for the first time study in the galaxy visible almost face-on the characteristics of gas high above its plane.

Note that there are no star clusters, supernova remnants or X-ray sources inside the classical cavity no. 107, surrounded by a strongly marked gas and dust shell. An arc of HII regions is located along its southern boundary. Judging from the normal ionization parameters in them, the respective young stellar groups were not formed directly under the effect of pressure of the expanding gas shell, but rather upon reaching a sufficient density of the swept up gas. However, there arises the question of how long the spectral features of the shock ionization are maintained.

However, stellar groups are present inside several cavities in NGC 6946. This way, inside (but not in the center) of cavity no. 85 there is a strange star complex with a diameter of about 600 pc, bounded on the west by a regular semicircle, which is reigned by a supermassive young cluster, by contrast not located in its center [8]. We hypothesized that this peculiar complex with its supercluster and the asymmetric cavity (Fig. 1), in which it is immersed, could form as a result of impact of a dark mini-halo [10].

A seemingly striking correlation between the intensity, radial velocity and excitation parameters of the ionized gas in various regions inside and near this complex, discovered in [10], can now be simply explained by the fact that at the decreasing emission intensity from NGC 6946, the EDIG our Galaxy makes a more and more growing contribution into the line profiles and intensities from the foreground gas of the Milky Way, which has much lower radial velocity than that measured in the gas of NGC 6946, the fact we were previously unaware of. This,

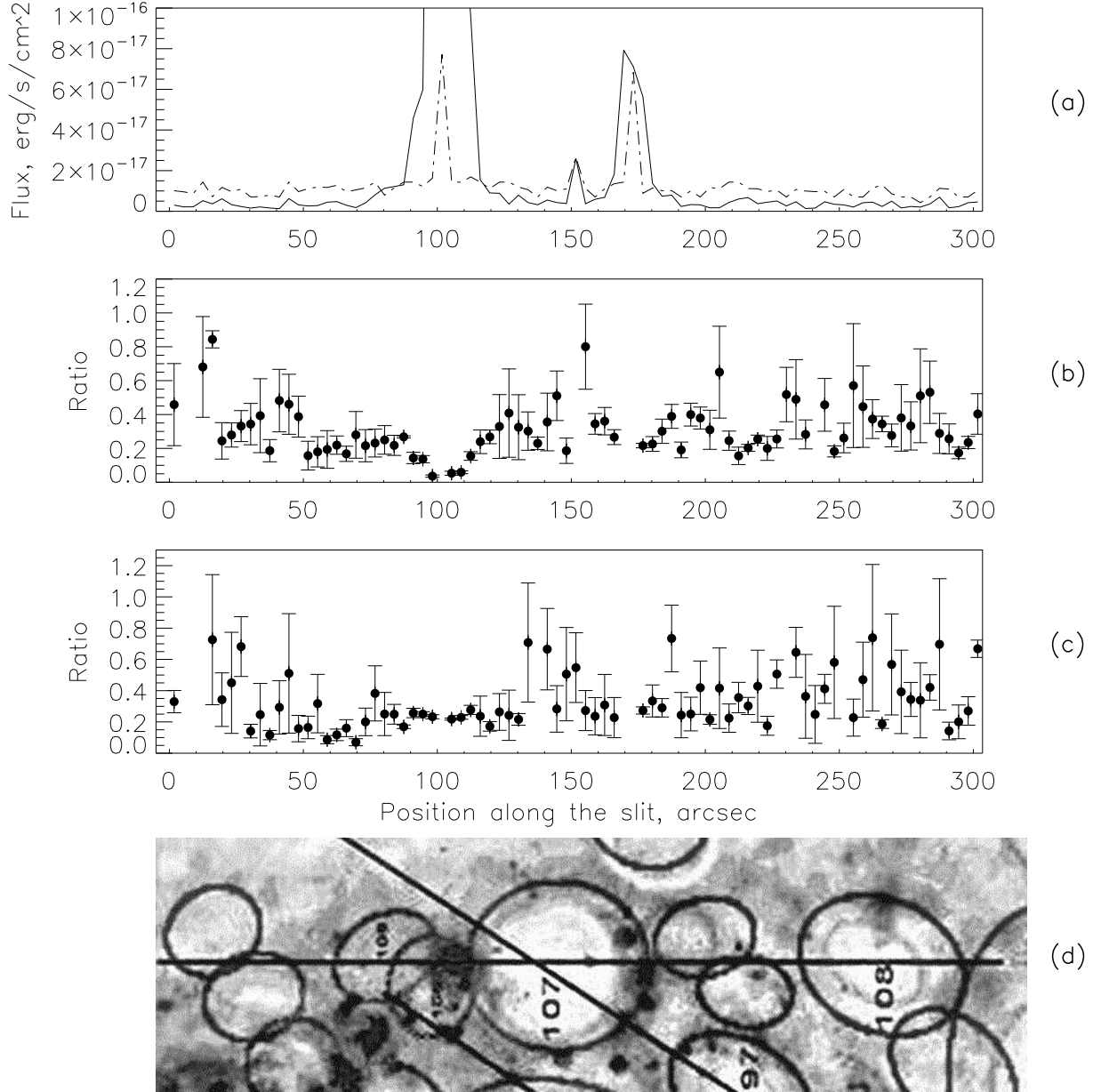


FIG. 10: The variations of spectral characteristics along the slit PA 180, passing through the cavity no. 107. (a) the fluxes in the [NII]  $\lambda 6583$  line from NGC 6946 (the solid line) and the WIM of the Galaxy (the dash-dotted line); (b) the flux ratio in the [SII]  $\lambda 6717/\text{H}\alpha$  lines; (c) the flux ratio in the [NII]  $\lambda 6583/\text{H}\alpha$  lines; (d) the slit position in the image of the galaxy in the line of HI with respect to the HI cavities. The HII regions are outlined in black.

obviously, applies to several results from [11]. A comparison of Fig. 5 from this work with the image of NGC 6946 in the infrared range shows that in this figure the velocities below 80 km/s are only observed in the mini-cavities visible in the warm dust.

The measurement of radial velocities from the profiles, obtained with a low spectral resolution, without separation into components, coming from the Milky Way and from NGC 6946 results in a decrease in radial velocities, and an increase in the relative intensity of forbidden emission lines in the regions with low

gas density of NGC 6946. This explains (but perhaps only partly) the features of the deep dip inside the peculiar complex, noted but unguessed in our previous work [10].

Since, as shown in [11], the peculiar complex as well contains the expanding gas shells, a wall of one of which is moving in our direction (detected as early as in 2002 [9]), it is likely that the deep dip [10] is real. However, its parameters and, above all, the real depth of the depression, the maximum approach velocity of its shell (or the rate of one-way gas outflow from it), have yet to be

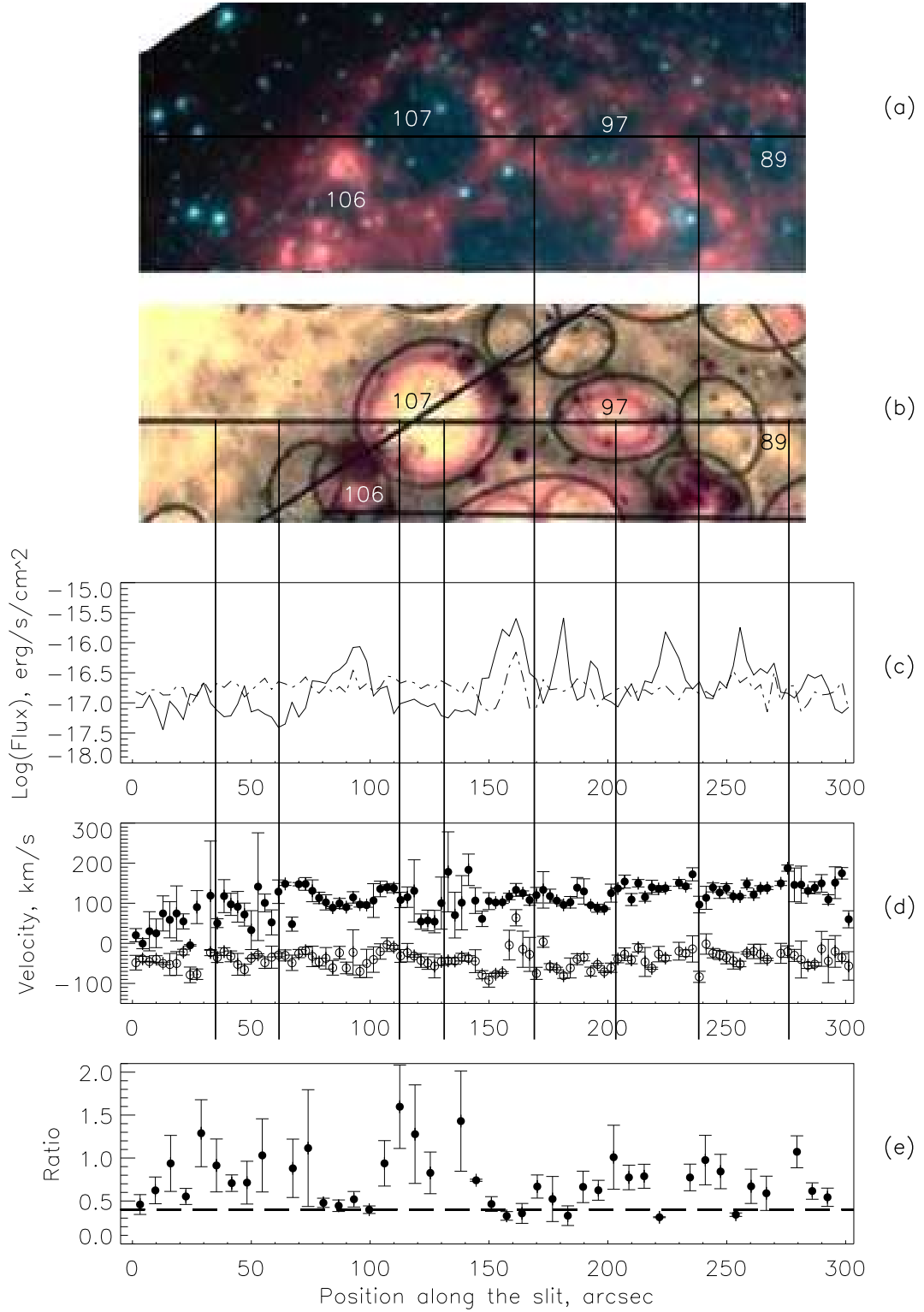


FIG. 11: The variations of spectral characteristics along the slit PA 147, passing through the cavity no.107: (a) the image of the galaxy based on the data obtained by the Spitzer telescope in the far IR region (see <http://www.spitzer.caltech.edu/images/2078-sig08-008-The-Fireworks-Galaxy-NGC-6946>); (b) the positions of HI cavities, found in [3] in the image of the region in HI 21 cm. The numbers of several regions are marked; (c) the fluxes in H<sub>α</sub> from NGC 6946 (the solid line) and the WIM of the Galaxy (the dash-dotted line); (d) radial velocities of ionized gas of the galaxy NGC 6946 (the upper curve) and the WIM of the Galaxy (the bottom curve) in the H<sub>α</sub>; (e) flux ratio in the [SII]6717+6731/H<sub>α</sub>. lines. Vertical lines indicate the features of the gas density, the line ratios and/or the radial velocity dispersion, the two longest lines end at the top in the mini-cavities of warm dust, almost invisible in HI due to the inferior resolution at 21 cm, but tangible as the local H<sub>α</sub> flux minima and as local the maxima of the ratio [SII]/H<sub>α</sub>.

evaluated anew, taking into account the intensities and velocities of the ionized extraplanar gas of the Milky Way, the presence of which we have asserted in this paper.

The sizes of large cavities (of almost all of them in NGC 6946) exceed the thickness of the gaseous disc in spiral galaxies, which is a great challenge for the conventional theories of their formation. As noted by Boomsma et al. [2], the groups of hot stars which may be responsible for the formation of cavities are observed only in two or three cases in NGC 6946. The problem has been studied long and intensively (see, e.g., [1, 3, 4]), but the causes of cavity formation remain controversial. In any case, the gravitational impact of a mini-halo of dark matter [7] is the most probable cause of formation of the cavity no. 85, and the peculiar stellar complex, located on its edge [10].

## VII. CONCLUSIONS

We therefore conclude that the cavities in the gas and dust disc of NGC 6946 allow us to observe the EDIG/WIM of our Galaxy—the extraplanar gas in the projection on the plane of the galaxy. Obviously, we can only notice the presence of this gas projected on such regions of the disc of NGC 6946, where the density (emission intensity) of gas with “normal” line ratios is small, i.e. projected on the disc cavities. We are not yet aware whether such an “anomaly” of the line intensity ratio was ever observed inside the cavities (more precisely, as we assume, projected on the cavity) in other galaxies. To verify our findings, we plan similar observations of several nearby spiral galaxies.

Across the disc of NGC 6946, we found two components in the radial velocities of lines of ionized gas—besides the component with varying intensity and velocity, ionized gas with almost constant radial velocity on the average amounting to  $-40$  km/s is present throughout the galaxy. The flux of the latter component varies along the slit only slightly and randomly, just like the line ratios, and its spectral characteristics are close to those, observed in the warm diffuse gas high above the Galactic plane. There is no doubt that this component originates in the Milky Way at high  $Z$ -coordinates.

What we observe in the projection on the cavities of the gas and dust disc of NGC 6946, is the EDIG of this galaxy, located high above its plane. That explains the typical EDIG/WIM ratio of the  $[\text{SII}]/\text{H}\alpha$  lines, exceeding

$0.4$ , which is observed in all without exception, cavities of various sizes (including such minuscule holes, observed only in the warm dust in the images obtained with the IR Spitzer Space Telescope).

The formation of cavities (bubbles, holes, shells, super-shells) in the galactic discs of neutral hydrogen is usually attributed to the fallout of fast gas clouds on the disc, or to the effect of the supernova explosion energy and stellar winds from hot stars on the surrounding gas. The second hypothesis is however confirmed only in few cases, and does not pass as a general rule. In particular, the arguments against it include the usual lack of appropriate clusters inside the cavities, and the fact that no cavities are revealed around a great number of star clusters of suitable age and luminosity [6].

We have to finish our paper stating that we have found the need to exclude the emission of extraplanar gas of our Galaxy in the study of NGC 6946, but found no signs of expanding cavities/shells in the gaseous disc of the galaxy, nor the evidence of collision ionization in the HII regions, bordering the cavities. Somewhat surprisingly, we saw these evidences inside the cavities, and most probably above them. A double conspiracy of spectral lines of ionized gas in NGC 6946, showing the signs of shock excitation not in the regions expected is a subject of further investigation.

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- [1] R. Boomsma, Thesis, <http://dissertations.ub.rug.nl/faculties/science/2007/r.boomsma/>
  - [2] R. Boomsma et al., *A&A* **490**, 555 (2008).
  - [3] I. Bagetakos, E. Brinks, F. Walter, et al., *AJ* **141**, .23 (2011).
  - [4] D. R. Weisz, E. V. Skillman, J. M. Cannon, et al., *ApJ* **704**, 1538 (2009).
  - [5] G. Tenorio-Tagle and P. Bodenheimer, *Ann. Rev. A&A*

- 26**, 145 (1988).
- [6] Yu. N. Efremov, *A&A Trans.* **21**, 251 (2002).
- [7] K. Bekki and M. Chiba, *ApJ* **637**, (2006).
- [8] S. Larsen, Yu. N. Efremov, B. G. Elmegreen, et al., *ApJ* **567**, 896 (2002).
- [9] Yu. N. Efremov, S. A. Pustilnik, A. Y. Kniazev, et al., *A&A* **389**, 855 (2002).
- [10] Yu. N. Efremov, V. L. Afanasiev, E. J. Alfaro, et al.,

- MNRAS **382**, 481 (2007).
- [11] M. Carmen Sánchez Gil, E. J. Alfaro, and E. Pérez, ApJ **702**, 141 (2009).
  - [12] N. M. McClure-Griffiths, A. Ford, D. J. Pisano, et al., ApJ **638**, 196 (2006).
  - [13] V. L. Afanasiev and A. V. Moiseev, Astron. Lett. **31**, 194 (2005).
  - [14] F. Bonnarel et al., A&A **189**, 59 (1988).
  - [15] A. D. Chernin, Yu. N. Efremov, and P. A. Voinovich, MNRAS **275**, 313 (1995).
  - [16] A. Moiseev, I. Karachentsev, and S. Kaisin, MNRAS **403**, 1849 (2010).
  - [17] L. M. Haffner, R. J. Reynolds, S. L. Tufte, et al., ApJS **149**, 405 (2003).
  - [18] J. A. Collins and R. J. Rand, ApJ **551**, 57 (2001).
  - [19] S. Silich, T. Lozinskaya, A. Moiseev, et al., A&A **448**, 123 (2006).

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