Internal Proper-Motions in the Eskimo Nebula

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ABSTRACT

We present the internal proper motion measurement of more than five hundred positions of NGC 2392, based on images acquired with the WFPC2 on board of the HST for two epochs separated by 8.805yr. We measured the amount of motion of local structures in the nebula determining their relative shift during that interval. We compared two different methods to determine the proper motions. Using those proper motions and the radial velocity taken from high-resolution spectroscopic observations, we were able to estimate a distance of 1050 pc .

1- Observations

1.1- Hubble Space Telescope Data

The observations were retrieved from the HST archive: 1998 December 1 (Kazimierz Borkowski) and 2007 September 21 (Bruce Balick). The images were obtained with the WFPC2, with exposure time 400 s, using the F658N filter. Figure 1 shows the difference of the two images taken 8.805yr apart (epoch-1 image 2007 – epoch-2 image 1998). In the difference the motion in the central bubble shows as "negative/positive" double ridge structures.

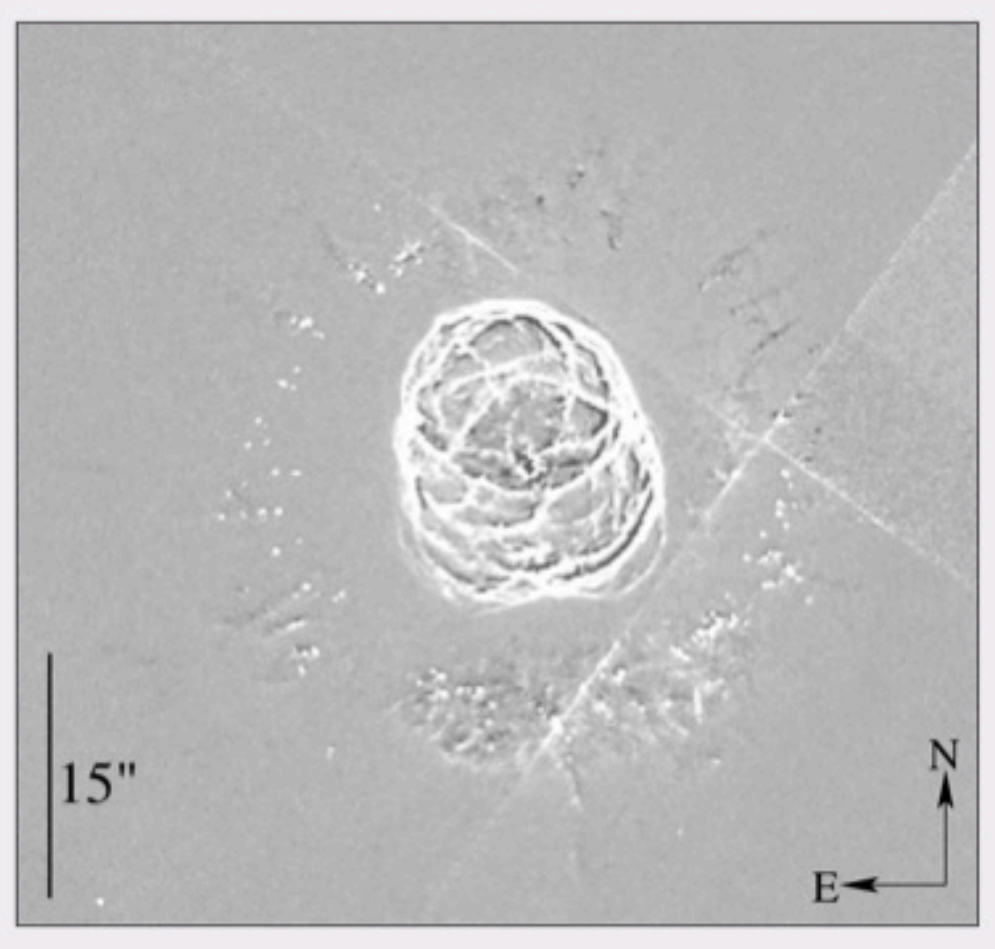

Figure 1

1.2- High-resolution spectroscopy

The observations were carried out using the MES-SPM spectrometer attached to the 2.1 m telescope at the Observatorio Astronómico Nacional, San Pedro Mártir, México. Figure 2 shows the location of each slit position on a [NII] WFCP2-HST image. Those data were used in the preparation of the paper García-Díaz et al. (2012, hereafter Paper I).

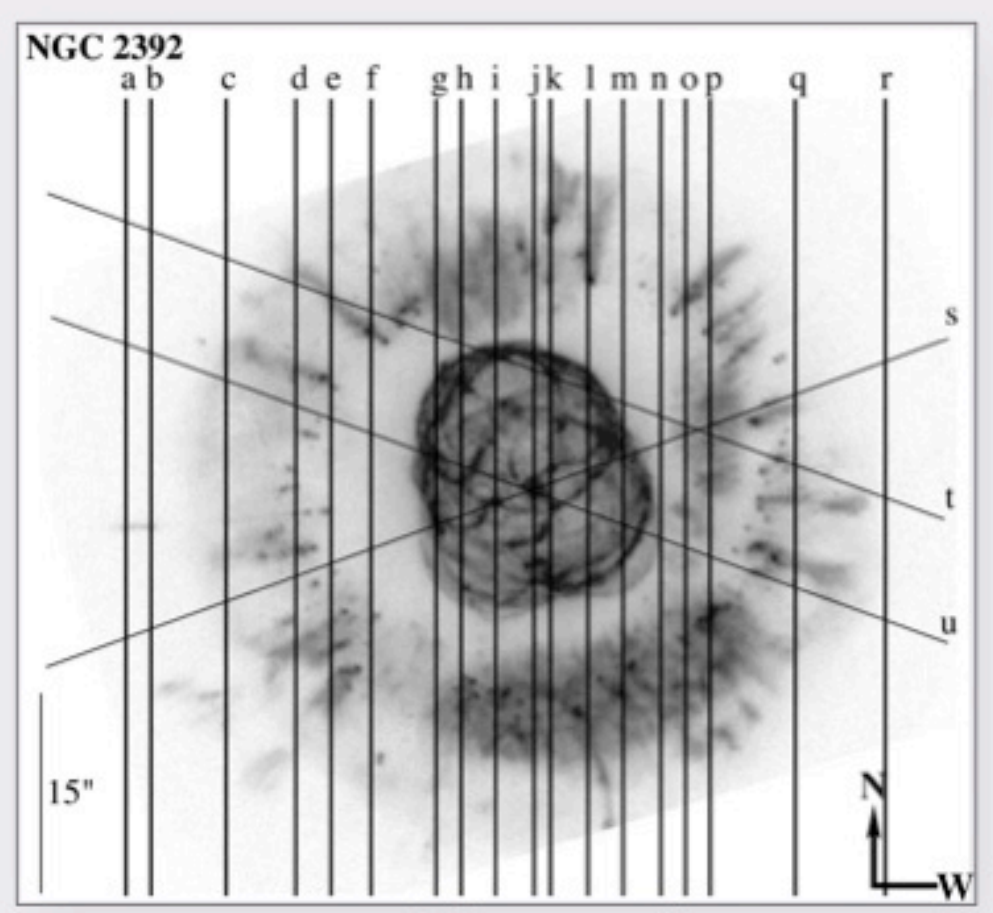

Figure 2

2- Measurement Technique

We used two methods based on the assumption that the proper motion of any local structure in a nebula due to expansion can be measured by determining the amount of translational shift of the structure.

First method: This method is based on the minimization of chi-squared. We identified 535 different local regions distributed throughout the nebula in the epoch-1 image. To analyze each section, we built a custom IRAF task to shift the section of one epoch with respect to the corresponding section of the other epoch, calculate the difference and estimate the chi-squared of the difference. The script repeats this process spanning from $-\Delta x$ to $+\Delta x$ and from $-\Delta y$ and $+\Delta y$. These values were programable in increments of 0.1 pixel. Visually we determined that the displacements are generally smaller than 1 pixel, and only in a few cases are greater, so we did several trials setting $\Delta x = \Delta y = 2$ or 3 pixels. Figures 3 and 4 show 3D plots of chi-squared. However, we found several cases where the calculated velocity vector was different from the real movement observed in an on eye blinking approach. The reason for this discrepancy could be the uncertainties in the determination of the displacements, given by the center of the surface of the chi-squared plot (See Figure 4), mainly in those places where the contrast in the image is not enough.

Second method: This method is based on cross-correlation. The definition of the cross-correlation function C_{fg} (i,j) normalized in a digital discrete image is given by:

$$\mathbf{C_{fg}(i,j)} = \frac{\sum_{\mathbf{x=0}}^{\mathbf{M}}\sum_{\mathbf{y=0}}^{\mathbf{N}}\left[\mathbf{f(x,y)}-\bar{\mathbf{f}}\right]\left[\mathbf{g(x-i,y-j)}-\bar{\mathbf{g}}\right]}{\sigma_{\mathbf{f}}\sigma_{\mathbf{g}}}$$

Where f(i,j) and g(i,j) are functions representing the pixel values of the two images. M and N are the dimensions of the subimage used, and σ are their standard deviations. Then, C_{fg} (i,j) varies between -1 and 1. In this case, to calculate the velocity of a given point, we defined a box typically of size 15x15 pixels around those points, with p denoting the center of the box. This 15x15 pixels box is correlated with a box of the same size centered in p+δ in the other image. If we move δ so that $-\delta_{max} \le \delta_x \le \delta_{max}$ and $-\delta_{max} \le \delta_y \le \delta_{max}$, we can obtain a value for the correlation in each point, building in this way the function C(p,δ). The point with coordinates (δ_x,δ_y) where the function is maximum determines the displacement of the regarded structure. Calculating the cross-correlation for different displacements, δ, in one of the images, we can build the function $C(p,\delta) = C_{fg}(i+\delta_x, j+\delta_y)$. The resulting proper motion vectors are shown in Figure 6.

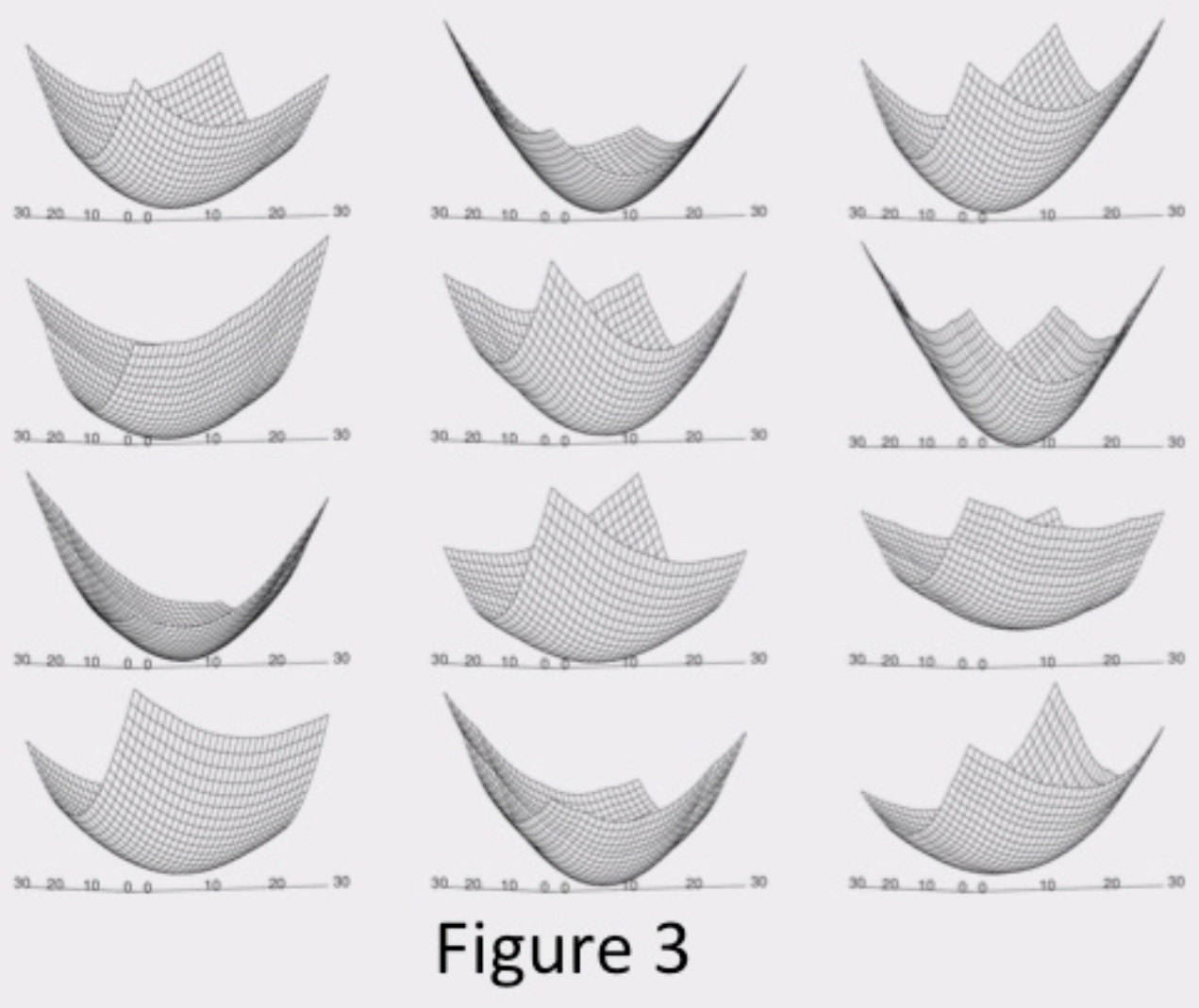

Figure 3

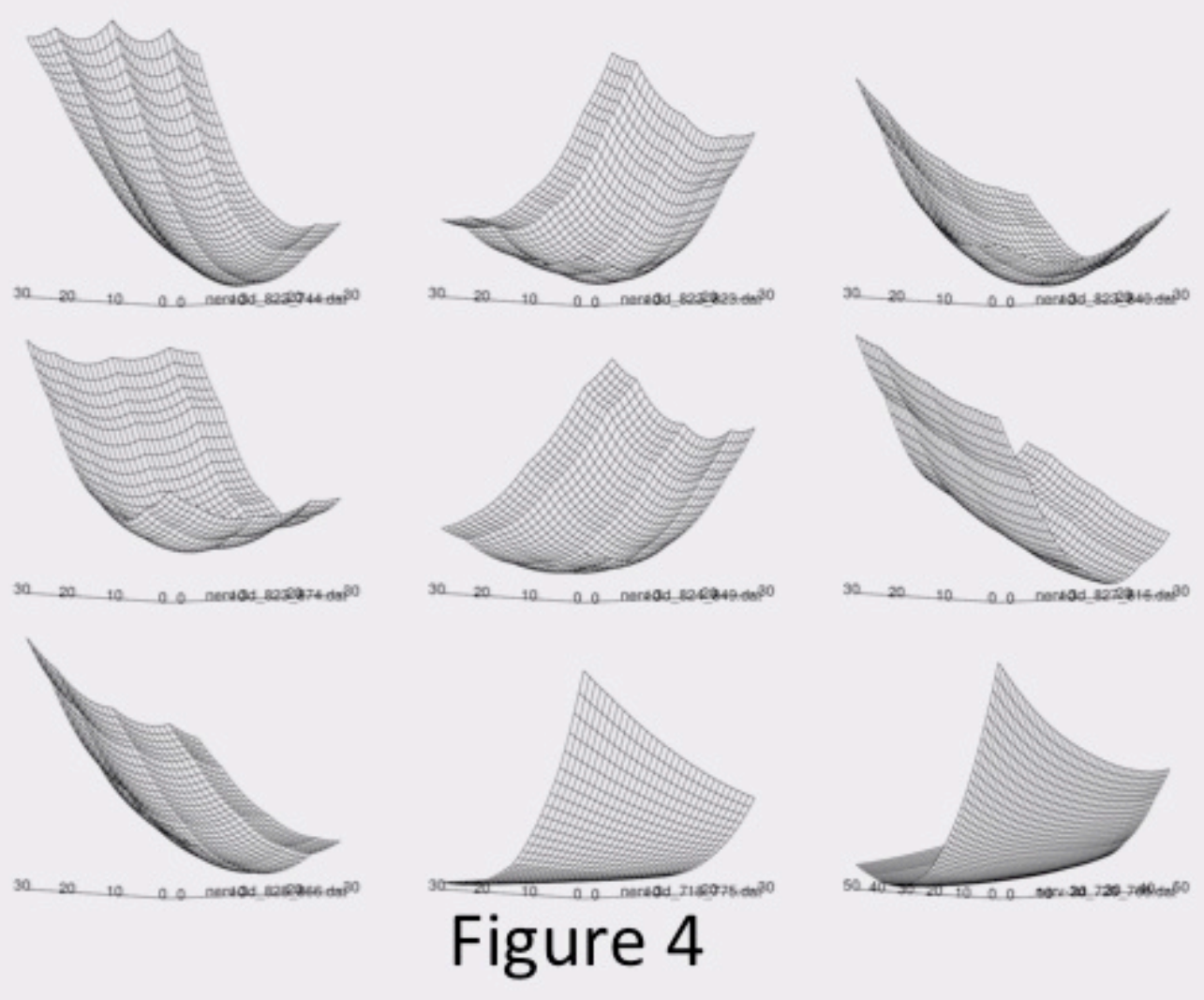

Figure 4

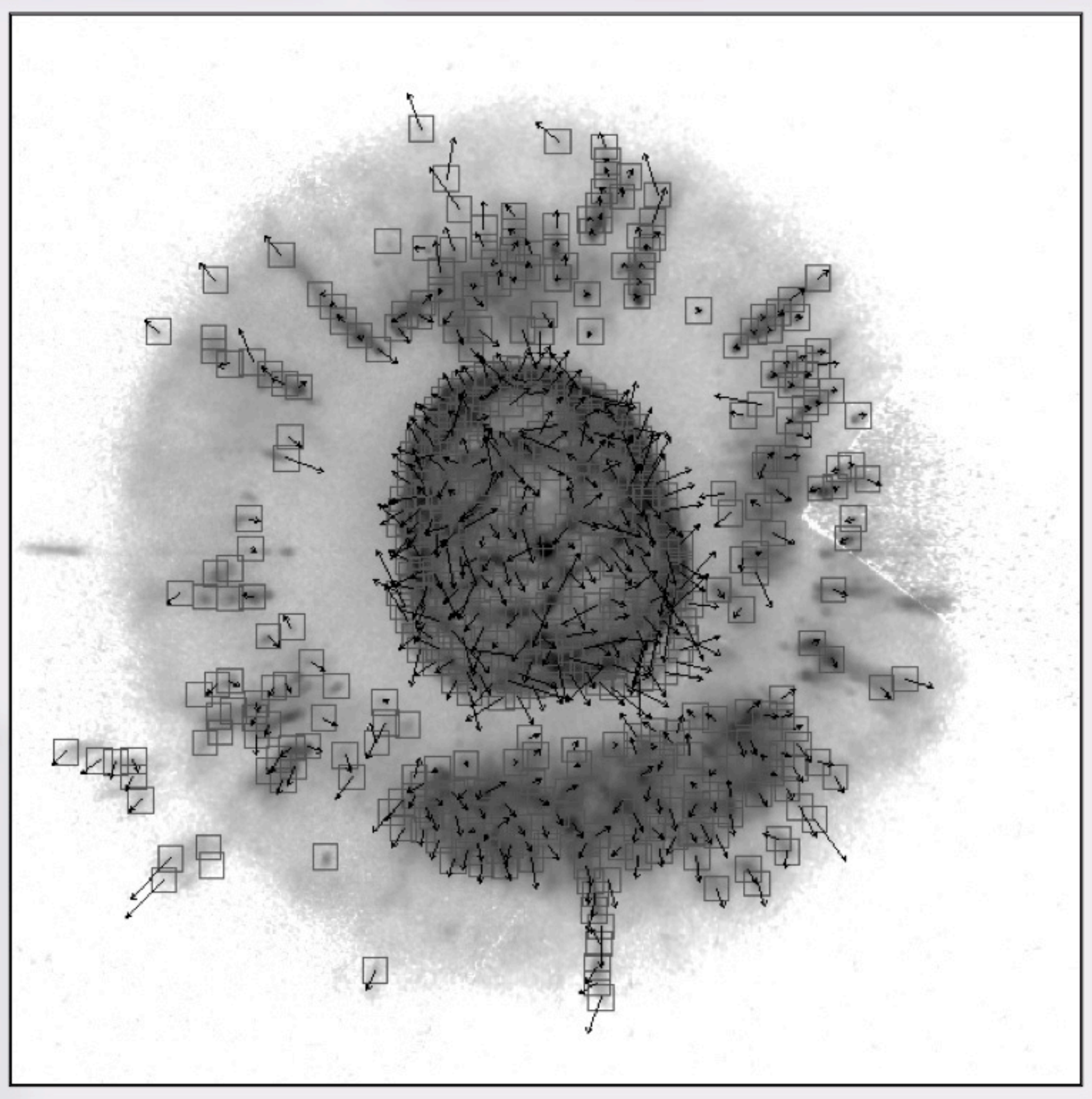

Figure 5. Chi squared method

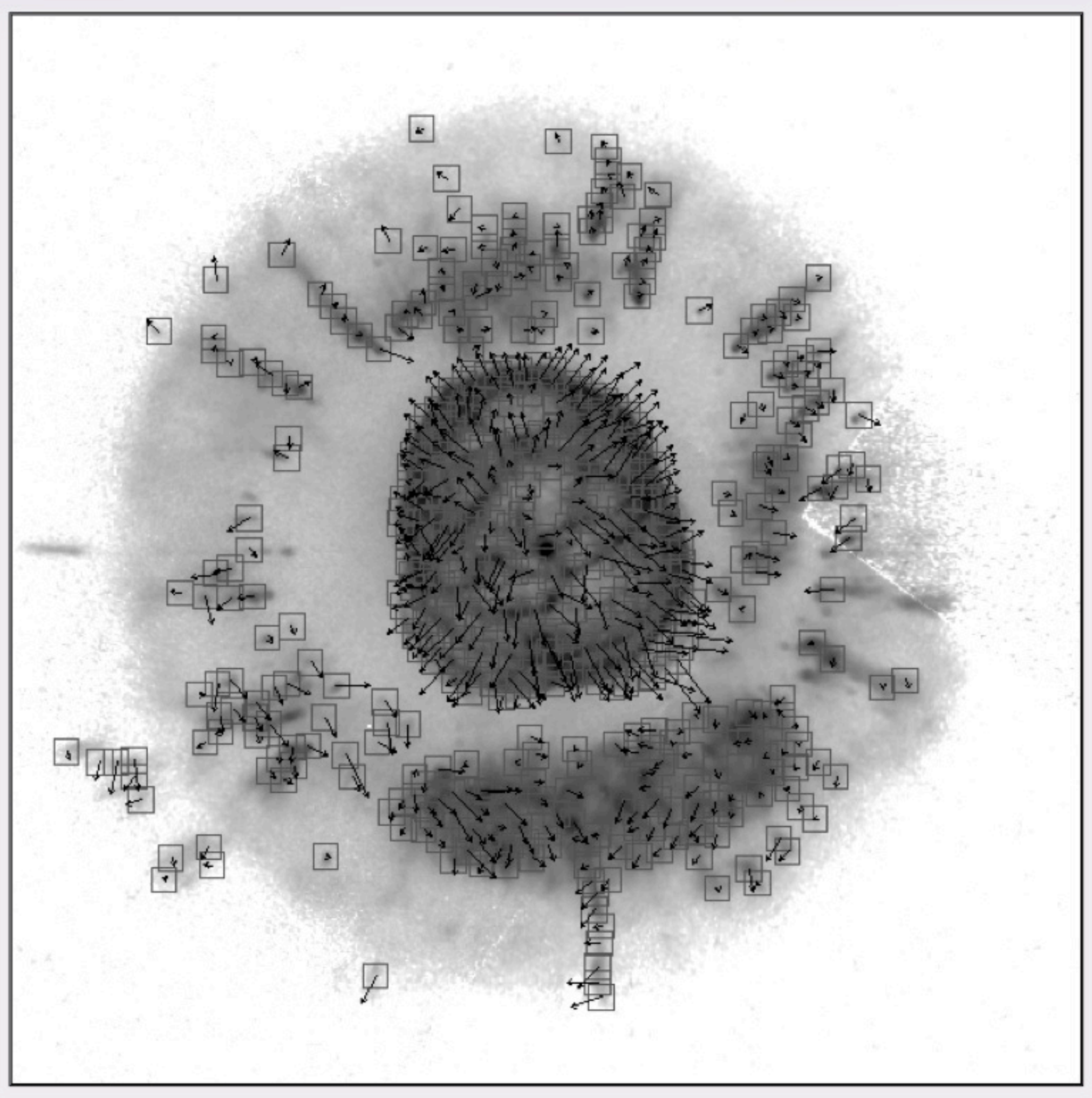

Figure 6. Cross-correlation method

3- Radial Velocities

The radial velocity of each local big structure was calculated using the [NII]6584Å line profile for 20 individual slit positions originally used for Paper I. In the position-velocity array shown in Figure 2 of Paper I, we identified several different regions distributed throughout the slit. Figure 7 shows an example of the distribution of the regions in slits *i – l*.

We calculated the heliocentric velocity for each region by fitting a gaussian to the 1-D profile. The radial velocities are then calculated by subtracting the systemic velocity .

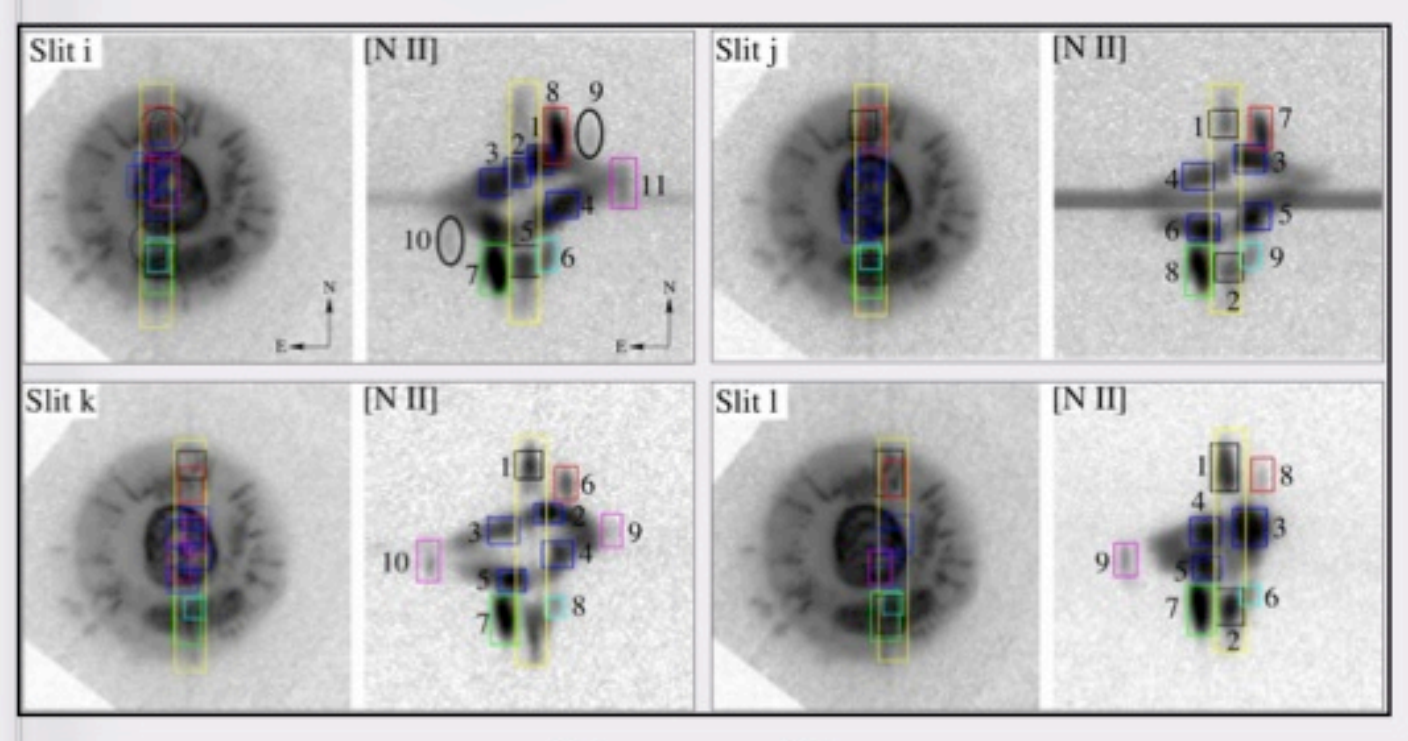

Figure 7

4- Distance

We consider that, statistically, the RMS of the proper motions are 0.4 RMS of the radial velocities, <rv>, due to the shape of the bubble as was modeled on Paper 1. It is possible to derive a relation to put the RMS of the proper motions, in km/s, given by,

$$\mathbf{D} = \mathbf{0.21095}\,\frac{\delta\mathbf{T}}{\langle\delta\mathbf{r}\rangle}\,\langle\mathbf{rv}\rangle\,/\mathbf{2.5}$$

From there, using all the motion vectors in the bubble calculated with the cross-correlation method, we find that the distance to the nebula is D = 1050pc.

5- Discussion about the two methods to calculate the proper motions.

We mesured the proper motions over than 500 regions of NGC 2392. On average, the values measured with the method based on the minimization of chi squared are a factor 2 greater than those calculated using the cross-correlation. We compared a set of regions where the contrast (measured as the higher values divided by the lower values) is high (>2), and the coincidence of the values found with the two methods is good at 40%. However, where the contrast is low, the discrepancy between the calculations is significant. Considering that the value of the distance obtained from the proper motions measured with the cross-correlation method is of the order of other values published, while the value obtained with the other method is too small (by a factor of 2), we think that the proper motions measured with the cross-correlation method are better, because, as we see in Figure 4 due to the shape of the chi-squared surface in many times it is difficult to choose a value for the location of the minimum with confidence.

5- References: García-Díaz, M. T., López, J. A., Steffen, W., & Richer, M. G. 2012, ApJ, 761, 172