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The Structure and Statistical Characterization of HI Gas

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Abstract. The great majority of HI feature studies are targeted observations of supernova remnants, stars with strong stellar winds or star forming regions. There have been very few attempts at searching HI surveys for new types of objects. This paper will describe first steps toward establishing a procedure for the taxonomy of HI features in the Galactic plane without any type of filtering. The aim is the classification within families characterized by the physical origin of the feature (e.g. dissociation of molecular gas). It is argued that the form of the brightness temperature distribution of a given feature is dependent on the physical process that created it.

1. Introduction

During this workshop many pictures of the neutral atomic phase of the interstellar medium (ISM) were shown. One's thought must have been "chaos" after seeing most of the images. Indeed the HI gas was assembled into irregular and interconnected structures having no preferred scales. However I believe that this complexity can be untangled because many of the energetic processes at work in the ISM (Alfven waves, shock fronts, spiral density waves...) are organizational. To succeed in this goal there is a need for an excellent database (the CGPS) and for proper tools of investigation. I explored resources provided by statistics and applied some of them on the brightness temperature distribution of HI features.

This paper expands on some aspects of an article soon to appear in the Astrophysical Journal (Ghazzali et al. 1999, hereafter Paper I) and is divided in three main sections. The first one contains a review of the physical processes that shape the ISM. A theoretical review of these processes is given in the second section in order to determine if they leave behind features with different density distributions. Finally statistical approaches are investigated to verify their usefulness in identifying the physical origin of given HI features.

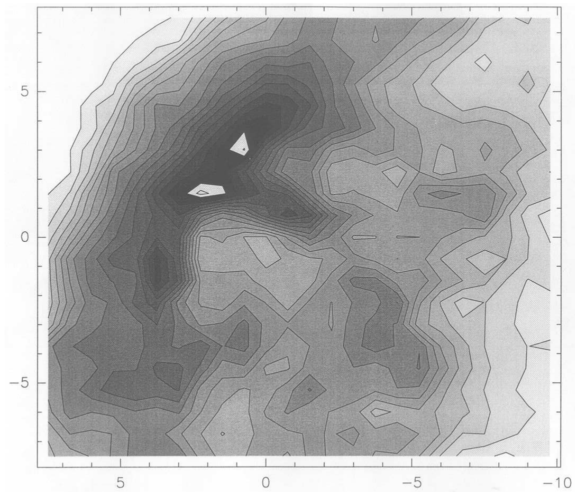

Figure 1. A grayscale integrated HI map (-14.18 to -19.12 km/s) of the photo-dissociated HI around the Sh 187 HII region. The contours are 3000, 5000,... K km/s.

2. The Sculptors of the ISM

Everyone knows that the global distribution of HI gas in a galaxy like ours is determined by the spiral density wave and the bar's gravitational potential. Superimposed on this assembling process (and originating from it) exist the massive stars (B4 and earlier). These stars bring disturbances in the spiral arms through three main processes:

1. Their copious emission of UV photons.
2. Their stellar winds.
3. Their explosion.

Turbulence may also shape the ISM but it is not clear at this time if it acts on all scales in a galaxy.

2.1. Star Forming Regions

Young massive stars produce HI features through (1) the photo-dissociation of molecular clouds and (2) the recombination of the ionized gas when the star's ionizing photons are too diluted or stop being produced.

A textbook example of the first case can be found in Joncas et al. (1992). The HII region Sh 187 is surrounded by a layer of HI gas whose distribution matches closely the one from the associated molecular cloud. (See Figures 1 and 2). Examination of Figure 6b from Joncas et al. (1992) shows the presence

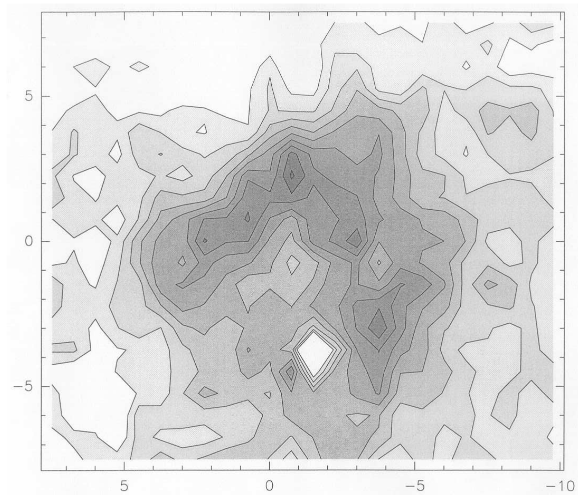

Figure 2. A CO integrated map (-12.4 to -17.5 km/s) of the same area, as in the Figure 1. The contours are 2.5, 5.0,... K km/s.

of a velocity gradient in the HI gas. This gradient is also present in the molecular gas. Its modeling implies an expansion with a velocity of a few km/s away from the exciting star (Joncas et al. 1998).

IC 1396 provides an example of another kind of interaction (Moriarty-Schieven et al. 1996). This HII region contains many bright-rimmed cometary globules. HI observations brought the discovery of ablated tail-like features behind the globules. The kinematics of the atomic gas is different from the molecular gas and seems to imply that the gas may have been pushed behind the globule by the action of the stellar wind where it lies protected from ionization by the UV photons. To my knowledge this recent discovery is still unique. Of the dozen or so HII regions observed in HI, the atomic gas has characteristics similar to Sh 187.

The second production mechanism has not been observed yet. It is my hope that the classification I am proposing will enable its detection.

2.2. Stellar Wind Bubbles

Many searches were made of HI shells around Wolf-Rayet stars with a high rate of success. However very few of these studies were done at high spatial resolution. To my knowledge only the work of Dubner et al. (1990) on the environment of HD 197406 provides enough resolution (2 pc) to enable the investigation of the distribution of the HI gas in the wind blown shell. It is obvious from their Figure 4, that the shell is asymmetric and shows large concentrations of matter in different parts of the shell.

2.3. Supernova Remnants

There is a vast amount of literature on the atomic gas associated with supernovae either of the survey type (e.g. Heiles 1979) or on particular objects. The latter is very diversified. One can study supershells (Maciejewski et al. 1996, their

Figure 3) and their impact on the galactic disk but the spatial resolution is often poor because of the very large size of these features (the Aquila supershell has a radius of 2°.8). The most interesting studies for the work presented here are high resolution work (1 pc) on postshock HI features (recombined gas) (e.g. Koo and Moon 1997, their Fig. 7 and 9) or the interaction of the shock wave with a pre-existing HI feature (e.g. Reynoso et al. 1995, their Fig. 7). The postshock gas distribution is more densely packed than the pre-existing more diffuse HI feature. Is this a trend?

2.4. Reflections

The survey of the literature for this work spans only the last 10-12 years. However I am confident in stating that all the above processes were only treated in a global way. Quantitative information was derived for the amount and thickness of dissociated HI and for expansion velocities, masses and kinetic energies of shells to check on different models. There is little description of the distribution of matter within the features even though its complexity is obvious.

Some very high resolution observations (0.02 parsec) were done on nearby HI features (Joncas et al. 1992, Moriarty-Schieven et al. 1997). These features are related to HI shells produced by an old supernova and have an intricate morphology of interwoven filaments. One might now ask whether all HI features are filamentary. Non-detection of filaments in other objects may result from a low spatial resolution. The answer is probably not. Brown et al. (1995) surveyed the Orion OB1 association with a resolution of 5 parsecs. Examination of their Fig. 6 and 7 show many filaments even at this low resolution.

The examples given above point to a diversity of morphology for the HI features related to the processes listed above. But morphology alone is not a sufficient criteria to distinguish the physics involved. The distribution of matter within the features appears to vary.

3. Do the sculptors have different genres?

In this section, a review of the theoretical literature is done in order to verify whether the distribution of HI is predicted to be different according to the physical process at work.

3.1. Massive Star Forming Regions

The UV photons emitted by the star(s) will erode the molecular cloud and form an HII region ionization bounded on one side and density bounded on the other if the HII region has evolved out of the molecular cloud.

On the intercloud medium side a "slow" supersonic shock front precedes the ionization front and sweeps up the diffuse gas (pressure from the expansion of the HII region also plays a role). As the gas moves further away the radiation from the recombination does not affect the dynamics of the neutral shell. This shell will become broader (∼150 parsecs) but is less energetic than those produced by stellar winds or SNs. When the UV photons are cut-off the HII region recombines and "joins" the shell with Champagne flow velocities. The distribution of gas is smooth unless encounters occur.

On the molecular cloud side there is a layer of HI originating from the dissociation of the molecular gas. As shown in the previous section the photo-dissociated HI conserves the imprint of the molecular material: clumpiness. Compelling work was done on the structure of molecular clouds. Williams & Blitz (1995) have determined the mass spectrum of a few clouds. Falgarone's impressive work has shown the presence of a hierarchy of scales down to 0.01 parsec at least (e.g. Falgarone, Puget & Pérault 1992). Wiseman and Adams (1994) have used topological tools to quantify the complexity of the column density distribution in many clouds. Photo-dissociated HI seems to keep this complex distribution of matter.

3.2. Stellar winds

Stellar winds literally blast through the ISM compared to the ionization phase. According to Draine & McKee (1993) the shock wave follows single fluid shocks theory where all components may be approximated as having a common flow velocity. Their Figure 1 gives a schematic view of the structure of such a shock. These shocks are relatively fast ($< 3\times10^2$ km/s) but most importantly they leave behind compressed gas with a density gradient perpendicular to the shock... a definite imprint.

3.3. Supernovae

SNs also blast through the ISM but the physics is somewhat different. The shock wave follows multi-fluid shock theory. The preshock gas is at least partially ionized having gone through the stellar wind bubble phase. The shock velocities are larger than 3×10^2 km/s. The density distribution in the postshock gas is undetermined but depends strongly on the magnetic field orientation and the thermal conduction of the gas. Because of the large energy involved in SNs the study of the interaction of the blast wave with an already existing HI feature is relevant. I would like to mention the work of Xu & Stone (1995) who investigated the theory of shock-cloud interactions. Their results imply that the cloud is transformed into a complex of filamentary structures. In addition Silich et al. (1996) were the first to take into account the evolution of a supershell within a clumpy medium.

3.4. Reflections

Albeit that the theory related to the aforementioned processes is still incomplete they *do* leave different signatures of their action in the density distribution of the neutral matter they leave behind. There are however caveats. All the postshock gases will eventually develop instabilities that may scramble these signatures. These instabilities may either be gravitational when a sufficient amount of gas has accumulated or been compressed or thermal when the conditions make the cooling time proportional to the temperature. Flow instabilities may also develop like Rayleigh-Taylor fingers at the expanding shell interface for SNs.

Turbulence may also be a major actor in the distribution of matter within any cloud or feature. Its presence was found in molecular clouds, HII regions and very probably in HI features. Being highly dispersive, turbulence will affect the gas behavior but their extent is unknown.

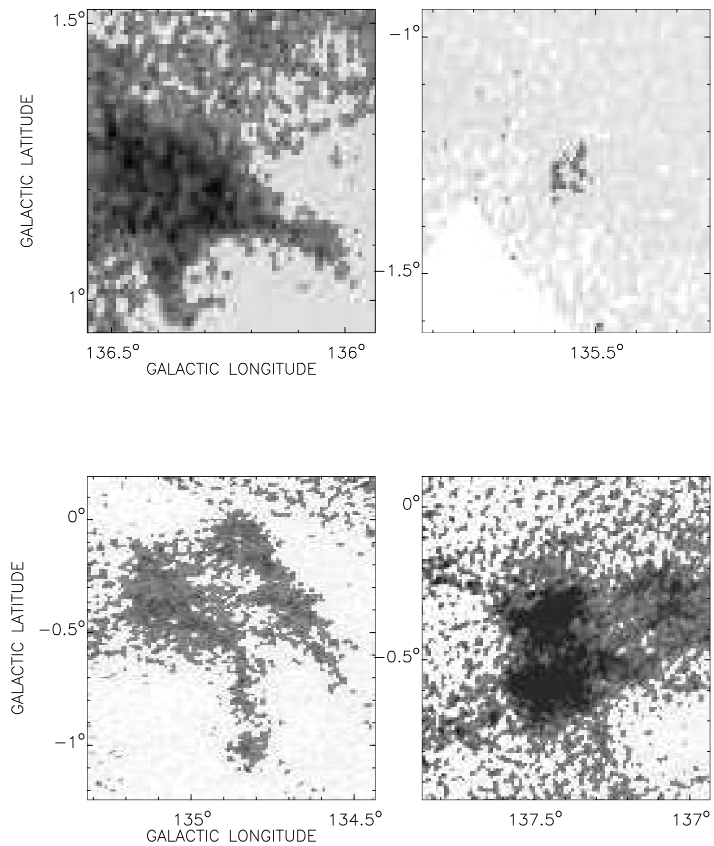

Figure 3. Grayscale maps of 4 of the HI features used for our classification scheme.

4. Can the sculptor be identified?

It thus appears that the form of the brightness temperature distribution of any HI feature is dependent on the physical process that created it. With this assumption I searched for tools to characterize these features for classification purposes using the distributions. The morphology and velocity structure of the gas is not taken into account in this first step. The goal is to develop the taxonomy of the HI features present in our Galaxy using a template of features of known origin. Figure 3 and 4 provides some examples of HI features while Figure 5 gives the corresponding brightness temperature distributions.

The first technique used is Principal Components Analysis (PCA). It is a reduction technique where sets of points of dimension larger than two are represented on lines or planes in search for relevant variables, the principal components. No assumptions are necessary and it suffices to build matrices where rows contain the brightness temperatures and columns correspond to the different objects. The results are described in Paper I. The technique is sensitive to both velocity and morphology gradients across the data cubes. PCA is also

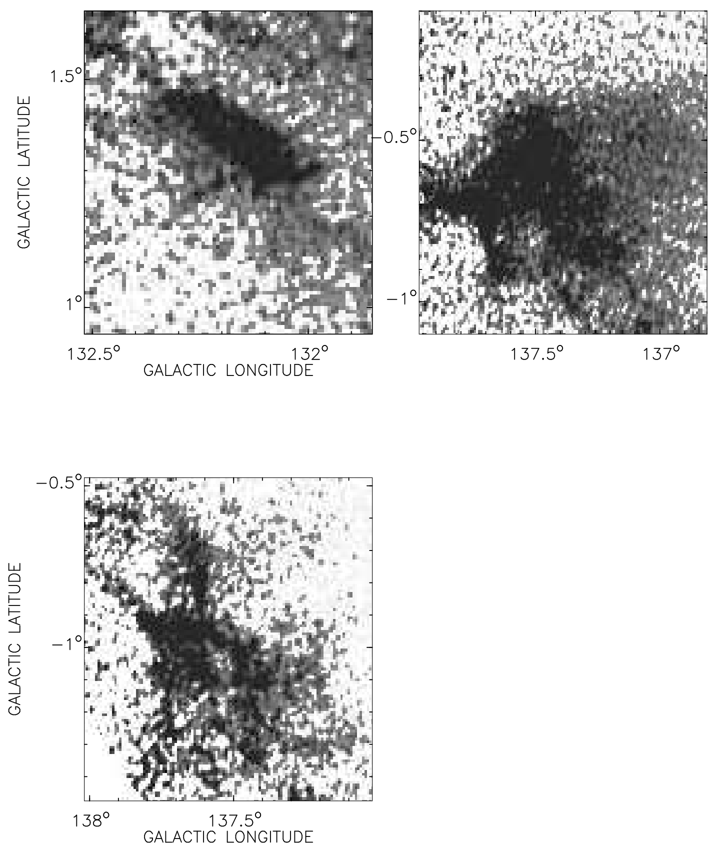

Figure 4. Grayscale maps of another 3 HI features. (Continuation of the Figure 3).

discussed in a paper by Heyer appearing in these proceedings. The technique is definitely useful for astrophysical analysis.

The second statistical tool that was used is called cluster analysis. It is the art of finding groups in data. The mathematical literature is abundant in papers proposing various techniques. The first one we used (Paper I) is the single and complete linkage algorithms. They are used most often in statistics. A distance matrix is built for the objects in order to derive their proximity to each other. It is a hierarchical clustering where the partitions (groupings) are based on the acuteness of the objects. This method has two weak points for astrophysical analysis: (1) the number of partitions provided by the algorithm is not unique opening the way to a biased interpretation and (2) the linkage has a chaining property as shown in Figure 6 hindering the partitioning process. Nevertheless families of HI features were found which more or less corresponded to varying physical origins. In this first step, we used only 2-D images of 21 different HI features.

We have very recently improved our procedure in a number of ways: (1) the feature extraction is more robust with respect to the noise level by using

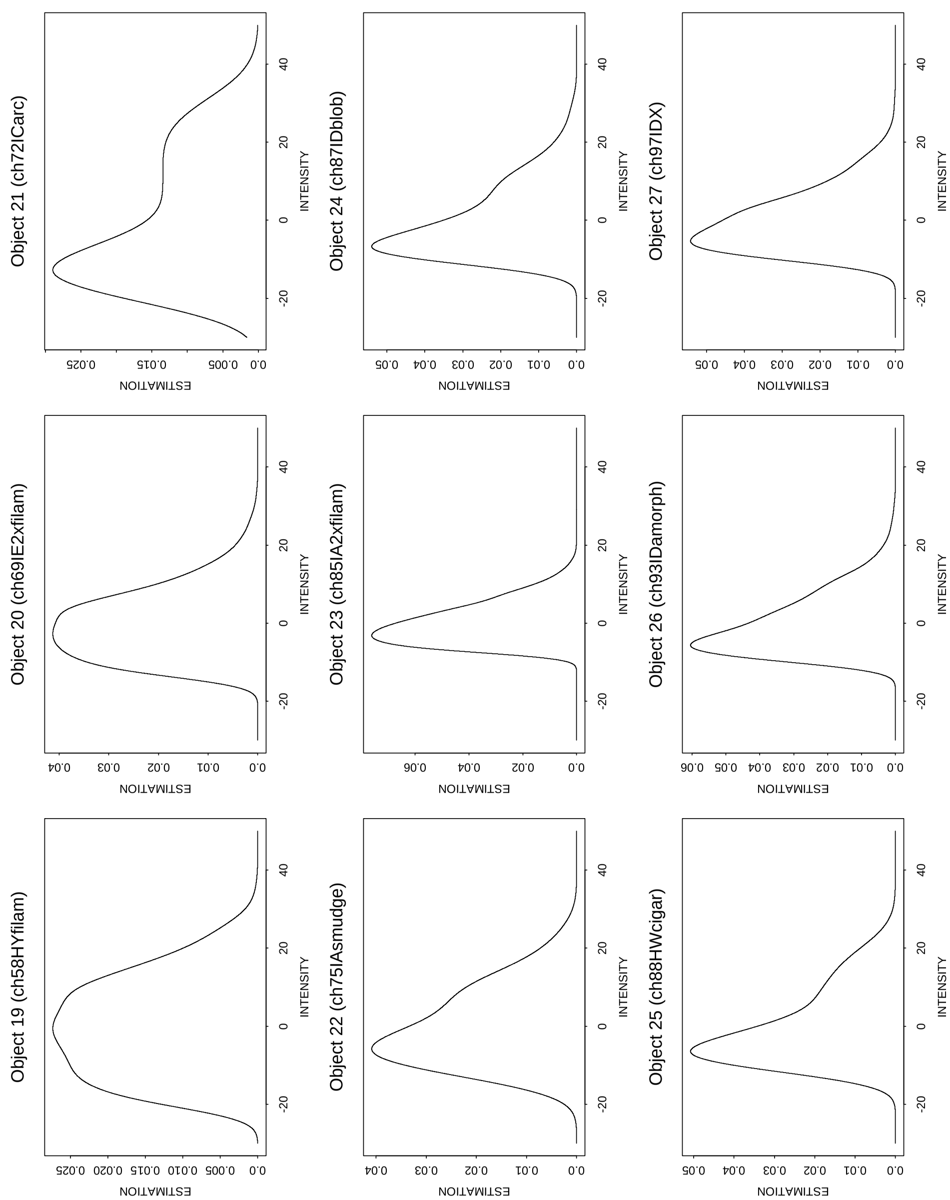

Figure 5. Estimation of the brightness temperature distribution of the HI features of Figures 3 and 4.

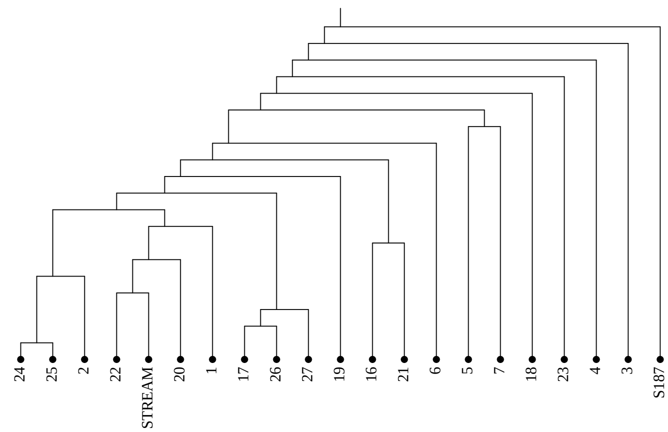

Figure 6. Dendrogram from the single linkage cluster analysis.

a minimum number of neighboring pixel in the connectivity algorithm, (2) the feature is now extracted in 3-D (position x position x velocity), (3) instead of being normalized the brightness temperature distribution are vertically scaled and horizontally displaced to minimize the dissimilarity with an arbitrarily chosen feature, this way differences in distances and backgrounds are dealt with (see Figures 7 and 8) and (4) a new clustering algorithm is used, fuzzy analysis (Kaufman & Rousseeuw 1990).

Table 1. Partitioning of HI features using fuzzy analysis (k=6).

Category	# of objects	identification
1	9	Be star, W5W, 4 shells, 3 filaments
2	8	3 models, 2 shells, 3 unknowns
3	12	W5E, S203, W4, 8 unknowns
4	9	HB3, 4 filaments, 3 models, 1 unknown
5	4	4 models
6	3	3 models

This algorithm does not make "hard" choices during the partitioning, it provides the user with a probability that a given object is a member of any group. This procedure is much more relevant to astronomy, it allows ambiguity. Who can say that only one process affects an HI feature! The drawback is that the number of groupings remains unknown. The calculations are done from $k = 2$ to $k = n/2$, where n is the number of objects. Figure 9 illustrates a hypothetical result: the objects are classified into three categories (A, B and C) where the dots represent groupings with high values of their membership coefficient for a given category and the Xs represent two objects with an ambiguous classification. The membership coefficients are derived using the dissimilarities between the distributions. The sum of all the coefficients is equal to one and all individual values are larger than zero.

The algorithm was used on the 21 objects of the Paper I plus 13 new objects and 14 simulations of HI shell bubbles. The results are reproduced in Table 1.

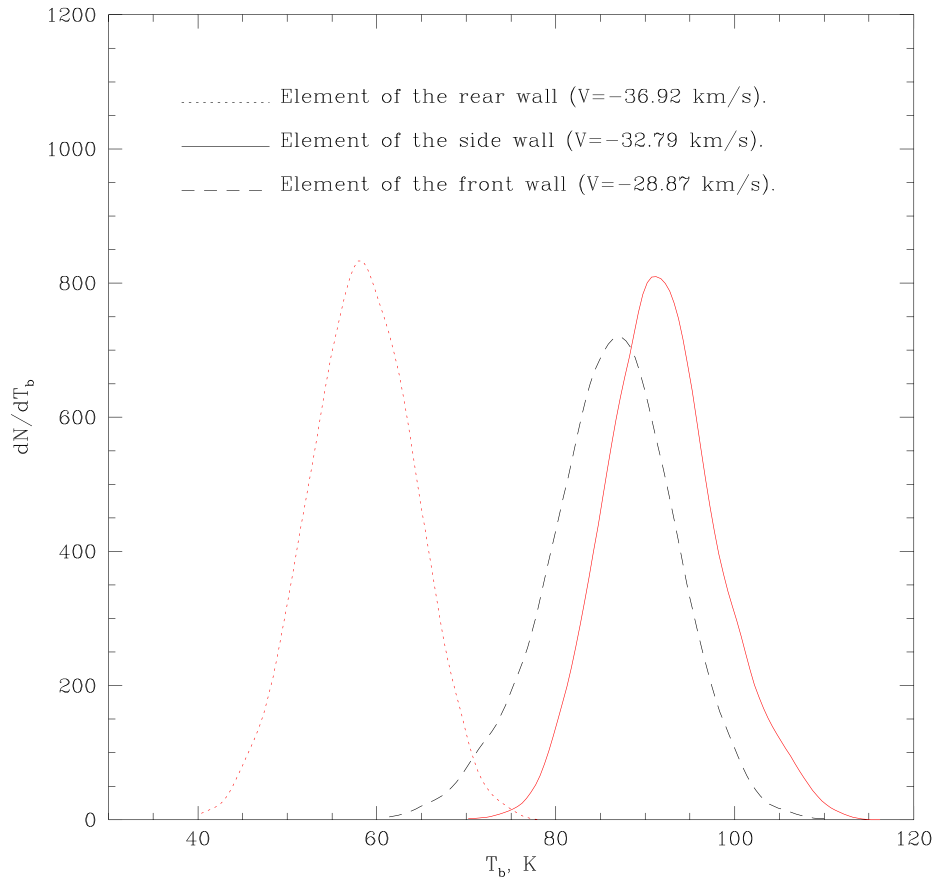

Figure 7. Estimation of the brightness temperature distribution of three pieces of an HI shell surrounding the Sh2-203 HII region with sizes of 0.25° x 0.25° x 0.412 km/s (50x50x5 pixels).

Group 3 brings together the three HI features associated with HII regions (W5E, S203, W3). Group 1 clusters the HI around a Be star with W5W, HI possibly pushed by a stellar wind from an O6e star. In group 4, the object named HB3 may be HI associated with an SNR. The shell objects resemble bubbles created by stellar winds. Clearly a proper number of template objects is still missing before we can declare the method successful. However the results are very promising.

5. Conclusion

Ultimately it is expected that such study will bring quantitative information about the energetics of our Galaxy by giving the proportion of features related to different energy input phenomena (e.g. stellar winds). As a side effect new types of HI features may be found. The long term goal is to establish an evolutionary

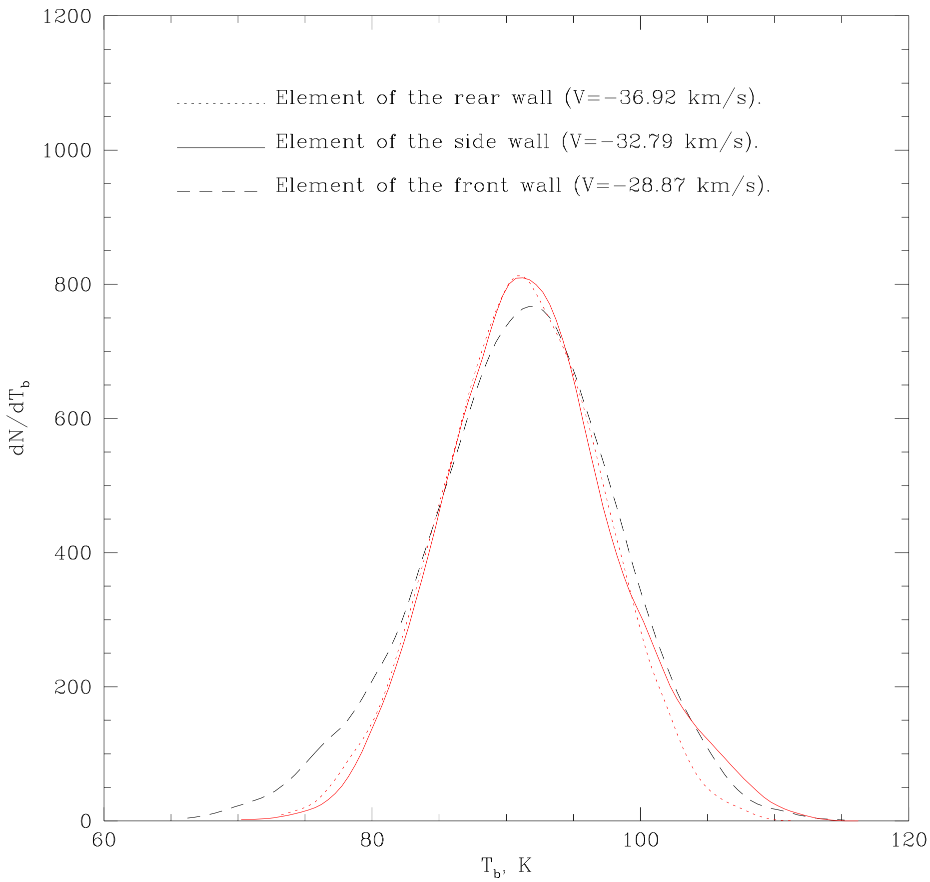

Figure 8. Modified distributions from the Figure 7. The invariants of cloud size (multiplier along Y axis) and constant background (shifting along X axis) were used.

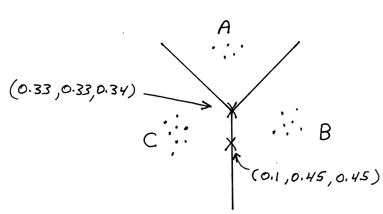

Figure 9. Example of a grouping under fuzzy analysis.

scenario where the diffuse HI gas is transformed into star forming molecular clouds and where the energy transfer and dissipation is integrated quantitatively.

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