SCALES OF STAR FORMATION REGIONS

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Abstract: Binary stars, trapezium systems, star clusters, OB associations, star complexes, supercomplexes and flocculent spiral arms: all of them represent different spatial scales of coherency in the star formation process. One of thee main questions in the study of how the stars are formed in galaxies is how to connect all these different scales into a basic scenario. During the last twenty years many people have been working to give a response to this problem, and now we have some answers. In this paper we discuss the structure in cascade of the different star formation scales and its connection with the arrangement of the galactic gas into clouds. We also analyze in depth two star complexes: one located in the spiral galaxy NGC 6946, and another located in the Milky Way with its center is close to the Sun, known as the Gould Belt.

1 Introduction

Star formation in galaxies occurs in a great range of spatial scales which are observed to be grouped around certain typical values. The age dispersion within these groups typically correlates with the size of the star forming regions, suggesting that star formation always proceeds withe a time scale of ≈ 2.5 crossing times in the progenitor cloud [1]. The main characteristic of these stellar groupings is that they present a hierarchical structure; i.e., each grouping of a higher order includes those of smaller sizes.

The highest level in the hierarchy of star formation processes was discovered by [2] analyzing the galactic distribution of Cepheid stars with similar pulsating periods and velocities. Efremov found groupings having sizes of about 400 pc and age ranges of about 50 Myr. They were called star complexes to distinguish them from the *associations* and *super-associations* of OB stars that show narrower ranges of age ($\sim$ 10 Myr) and size (5 times smaller in the case of associations).

Moreover, the analysis of the super-associations of OB stars in M31 made [3] consider that these super-associations were also star complexes that contained the typical OB associations.

Star formation complexes in our Galaxy have been isolated after studies of the distribution of young star clusters (Δt=30 Myr; r $\leq$ 6 pc) [4], WR stars [5, 6], Cepheid stars [2, 7] and associations [8]. These complexes reach sometimes diameters larger than 1 kpc, and thus they have been named *super-complexes*. The existence of complexes and super-complexes with a hierarchical structure has also been observed in irregular galaxies such as the LMC, where OB stars, star clusters and associations follow a hierarchical distribution too. But, what is the maximum size that a star grouping can reach while maintaining a spatial coherence in the processes of star formation? Obviously, that will depend on the distribution of gas in the galaxy and on the dominant star formation mechanisms. In fact, the definition of star formation complex was broadened by [9] to comprise the wide range of groupings that go from multiple stars to flocculent spiral arms. They also established that the maximum scale is defined by the disk length, where the shear time is comparable to the crossing time. [10] lies on this fact to propose that, this being the case, then there must be a few star complexes in a galaxy that show a characteristic length and mass, and that they contain groupings of associations and clusters in a cascade-like progression. Thus, it seems that the formation of these objects is necessarily linked to the formation of the largest gas clouds that can be found in a galaxy, which are mainly dominated by the characteristic scale length and the gravitational and magnetic instabilities of the gas.

In this article we shall review the spatial and kinematical distribution of the star complexes in our Galaxy and in other nearby galaxies. Our objective will be to establish observational constrictions for the different mechanisms of formation and arrangement of the clouds in spiral galaxies. We shall study in detail two singular star complexes: one situated in the galaxy NGC 6946, 6 Mpc away from the Sun; and another in which we are immersed and can be observed with the naked eye -as Herschel did in 1847-, known as the Gould Belt. It is evident that they are two stellar groups that have been studied using different observational methodologies; yet they show some common features that make us consider that we are witnessing the same kind of stellar system. Their comparative analysis can give us some clues about the formation mechanisms of these structures, and even about the veracity of their proper existence.

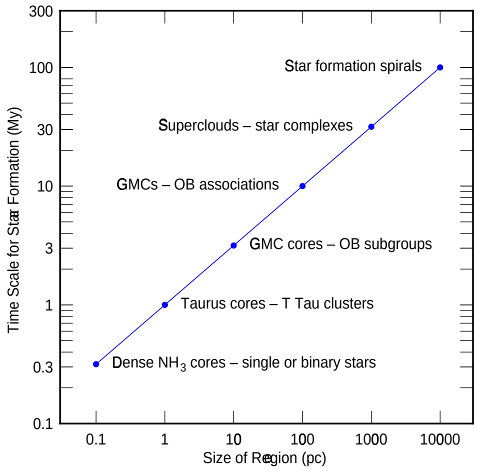

Figure 1: Correlation between the size and the duration of the star formation for the whole scale of sizes. The typical values corresponding to observed star forming regions are labeled in the plot. Reprinted from [1], with permission.

2 Masses, Sizes and Ages

The analysis of the sizes, age ranges and masses of a sample of star complexes in spiral and irregular galaxies yields a series of functional relationships. These relationships point to the following conclusions:

1. The age of the complexes ranges between several times 10^6 to 10^9 yr, with most complexes around the age of 10^7 yr. Their masses range between 10^4 and 10^7 solar masses [11].
2. There exists a clear correlation between the duration of star formation in a region and the size of the region. This has been clearly proved for the cluster distribution in the LMC for age ranges between 1 and 100 Myr [1], as shown in Figure 1.
3. Both the fractal size distribution and the size-duration correlation of the star forming regions show to be consistent with values predicted by theoretical turbulence models of the interstellar medium [11, 10].
4. Elmegreen et al. [12, 13] show that the hierarchical structures of the stars and the gas present similar power spectra (derived from optical sources and the HI distribution along azimuthal cuts in the LMC), thus supporting the

> previous conclusion. When the galaxy is a spiral, only the lowest wavenumber tail of the power spectra is affected by the spiral density perturbation, the remaining spectrum being similar to those in flocculent galaxies [10].

Thus, the star formation in galaxies seems to occur in a top-down cascade where the largest scale is defined by the largest gas cloud that can be formed in the galaxy. For galaxies where driving potentials other than turbulence are present (e.g. gravitational spiral potential, well-ordered magnetic field, central bars, etc) the gas clouds are also arranged into grand design structures (spiral arms, polar rings, etc) which dominate the general aspect of the galaxy. Otherwise, the size of the largest gas cloud appears to be roughly defined by three times the minor axis (projected onto the galactic plane) of the large-scale structures in the host galaxy.

3 Spatial and Kinetic Distribution along and across the Spiral Arms

3.1 Spatial Distribution

Although we have outlined a general scenario for the star formation in galaxies, we must engage in a more detailed discussion in order to better know how the complexes are formed and how the stars are born inside the complexes.

It is well known that the largest groupings of star formation tracers in spiral galaxies appear to be distributed along the spiral arms with a characteristic length of separation which correlates with some averaged properties of the host galaxy (e.g. [14]). This has been observed in the distribution of H_α regions [14], HI clouds [3], open clusters and WR stars in the Milky Way [15, 5, 6], Cepheid stars [16], etc.

In the early 90s, our group was working on the spatial distribution of the young stellar population in the Milky Way. We wanted to get some information about the stellar component of the Galactic warp. By using mine prospecting techniques (Kriging or Krigeage) developed to probe the gold mines in South Africa we got the first 3D map of the distribution of the young stellar component within a radius of 3 kpc around the Sun [4]; see Figure 1 in that paper). A very striking feature appearing in this map was a large (≈ 3 kpc along the major axis) and deep (Z≈ -150 pc) depression located in the third galactic quadrant, which we called the "Big Dent". In addition, three other lesser deep valleys were also observed, showing that the Galactic plane is far from planarity, even for the young stellar population. However the most outstanding result was that these valleys appeared to be spatially associated with the four main supercomplexes detected by [2] in the solar neighborhood from the distribution of Cepheid stars. From this 3D view we studied the distribution of the young stellar clusters along the Carina-Sagittarius arm, the most conspicuous grand design arm in the vicinity of the Sun, unveiling that this spiral arm, as defined by the young open clusters, shows a corrugated vertical structure about 50 pc in amplitude and 1.2 Kpc in spatial scale [5]. Similar results were found by [16] from the analysis of the spatial distribution of Cepheid stars. All these results led us to propose that:

- The main physical mechanisms shaping the 3D structure of the Galactic plane are intimately connected with those driving the large-scale star formation processes in the disk.
- The vertical structure of the Galactic plane suggests that at least two different kinds of mechanisms could be involved in the generation of these morphologies: one unpredictable, violent and very energetic, like High Velocity Clouds (HVCs)-disk collisions, which could explain the formation of structures such as the "Big Dent"; the other, affecting the whole Galaxy, which could be generated by the response of the disk to different types of perturbations, giving rise to the formation of the corrugated arms.

3.2 Kinetic Structure

Many different physical processes have been proposed as the driving forces for these corrugations (see [17]); but the main question is how to distinguish among them. The principal constraint to design an experiment able to discriminate among the different models is that we have only the Milky Way to analyze the 3D structure of the disk. When looking at external galaxies we are limited to 2D studies. However, all these models predict the generation of vertical velocity fields with a high degree of structure. In addition, these velocity predictions are different from model to model, so we have at our disposal a very good discriminative tool. Looking back among the literature in search for articles on vertical velocity fields in galaxies, practically nothing can be found, except for some recent studies of other galaxies by [18], and of the Milky Way by [19]. We wonder about the reason for this lack of information.

Roberts [20] showed that the encounter between a density wave and the gas disk could generate vertical motions with amplitudes always lower than 3 km s^{-1}. This caused that, *when HI observations of face-on galaxies showed extended velocity components with dispersions of the order of 20 km s^{-1}, they were attributed*

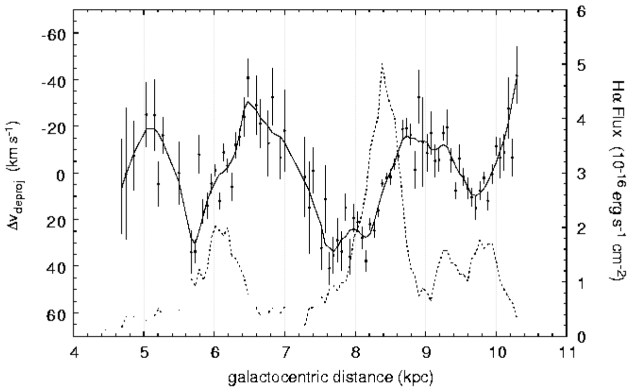

Figure 2: Deprojected residual velocity across a spiral arm in NGC 5427. The dashed line shows the spatial distribution of the H_α emission along de same cut.

to other phenomena, such us galactic fountains, a warping of the HI disk, or intermediate-velocity clouds, in words of [21].

The results by Roberts were correct, but restricted only to a very thin disk. But if a thicker disk, with a scale height of the order of 1 kpc, is taken into consideration, coherent motions with amplitudes larger than 20 km s^{-1} indeed appear. And the only ingredient needed to have such a thick disk is a magnetic field that is able to support this scale height by magnetic pressure.

In 2001 we analyzed the radial velocity field of NGC 5427 along a galactocentric radial direction [22]. We found a corrugated pattern that fitted very well the prediction of the models by Cox's team [21]. For the first time it was proposed that the vertical velocity field shows a corrugated pattern and that it was in good agreement with the predictions of some models.

At the same time, the hypothesis of a magnetized disk was becoming more and more fruitful. A Korean group in collaboration with the Mexican team of the UNAM addressed again the problem of the Parker instability, but this time they worked under more realistic assumptions about the magnetic properties of the gas (e.g. [23]). They found that:

- The Parker instability in a magnetized spiral arm arranges the gas forming

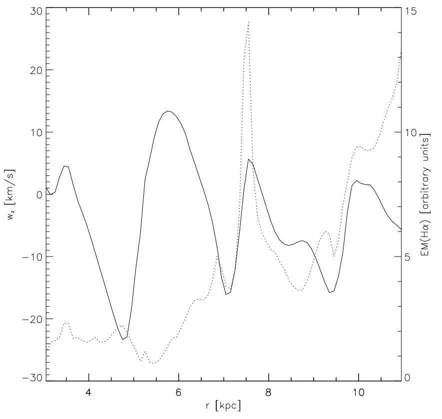

Figure 3: Same as in Figure 2, but for the corrugations expected from a simulation model of our Galaxy. Reprinted from [21], with permission.

clouds (with masses of 10^7 solar masses and sizes of 1 kpc), which appear distributed above and below the galactic plane in an alternate way.

- The mean separation between clouds is compatible with that observed in the Carina-Sagittarius arm, for similar physical conditions of the gas.
- A vertical velocity pattern along the spiral arm is also predicted by the model.

All these results, both theoretical and observational, seem to indicate two main evidences:

1. The hypothesis of a magnetized disk makes easier the agreement of corrugation models with observations.
2. The large gas superclouds, originated by magneto-gravitational instabilities in the disk, are the best candidates for progenitors of the big complexes observed in grand-design spirals.

Nevertheless, even the mere existence of corrugations in the velocity field is still controversial. Thus our team has designed an observational project mainly devoted to a single objective: to definitely prove the existence of velocity corrugations in the disk of face-on galaxies. This project must be accompanied by the development of several improvements in the model codes.

4 Singular Stellar Complexes

Another way to address the study of the origin and evolution of the star complexes is to analyze the nearby complexes in great detail. Why should this sort of objects be studied? The analysis of the stellar component and the physical conditions of the remnant gas for this kind of star formation regions could provide answers to these questions:

- What controls the switch between different star formation modes (i.e., either isolated stars or stars clusters)?
- What triggers the formation of massive clusters?
- And, how does the propagation of star formation proceed inside the complex?

To this aim, a multi-component and multi-wavelength study of some peculiar complexes has recently begun. In fact, only two star complexes have been extensively studied so far: The Gould Belt, a stellar system in the Milky Way in which the Sun is immersed (see [24, 25]); and another system harbored by the galaxy NGC 6946. We shall focus our attention in the star complex in NGC 6946, which has been analyzed from several points of view and at different wavelengths during the last years.

4.1 NGC 6946

NGC 6946 is a nearby galaxy located at 6 Mpc from the Sun which shows some special features:

- It has a very high Star Formation Rate (SFR) over the entire disk [26, 27].
- It shows a high density of star clusters, even thought it could be contaminated by foreground stars due to the low galactic latitude of the object ($b\approx 12^o$) [26].
- It is the galaxy with the highest number of observed SNs (8).
- Many very massive and energetic HVCs have been detected and associated with this galaxy.
- Two dwarf galaxies seem to be orbiting around it. A weak bridge of HI, starting at the outer disk and directed towards the projected position of the two satellites, could suggest that a third neighbor has merged with the main body.

But its most conspicuous feature is the presence of a large, blue and bright star complex located at the end of a sub-branch of one of the main spiral arms. This structure was first noted by [28] in 1967 and re-discovered by [26] thirty years later.

The complex

This star complex is 600 pc in diameter and is placed about 5 kpc to the South-West of the center of the galaxy (see Figure 4). The complex is also remarkable for its almost circular shape in Hα images. It contains, close to its geometrical center, a massive, young star cluster (of one million solar masses and about 15 My old) [11, 26].

In addition, there are a few dozens of less massive, but still young (between a few and 30 My old), clusters that have been detected inside the borders of the complex. The Star Formation History derived from HST stellar photometry shows that the current SFR is very high in this complex [27].

Different groups of ages are located in different regions inside the complex. Supergiants (25 My old) are concentrated around the center of the object, close to the super-massive young cluster (SMYC), while the youngest OB stars form an arc-shaped structure to the NW of the central cluster (see Figure 4) [27].

Long slit spectroscopy along three different directions passing through the massive cluster, suggests that the interior of the complex is far from being quiet, showing some small but very energetic structures [29].

3D Spectroscopy

New observations have been carried out, mainly directed at getting more information about the physical properties of the ionized gas. 3D spectroscopy of the complex was taken with the 6m telescope at SAO (Russia) and the William Herschel Telescope (WHT) at the Roque de los Muchachos Observatory in Spain. The preliminary analysis of the INTEGRAL data (with a size of 30 arcsec centered at the SMYC) taken with the WHT yields the following results.

The Hα map (see Figure 5) displays a drastic contrast between the emission coming from the outer ring and that generated in the NE side of the complex. As we see, the Hα image shows an almost circular emission shell surrounding the stellar component.

In Figure 6 we show the distribution of the fibers of the INTEGRAL instrument and, using a color code, the mean velocity per fiber, estimated as the average of the radial velocity (RV) for three different emission lines. When the S/N ratio of

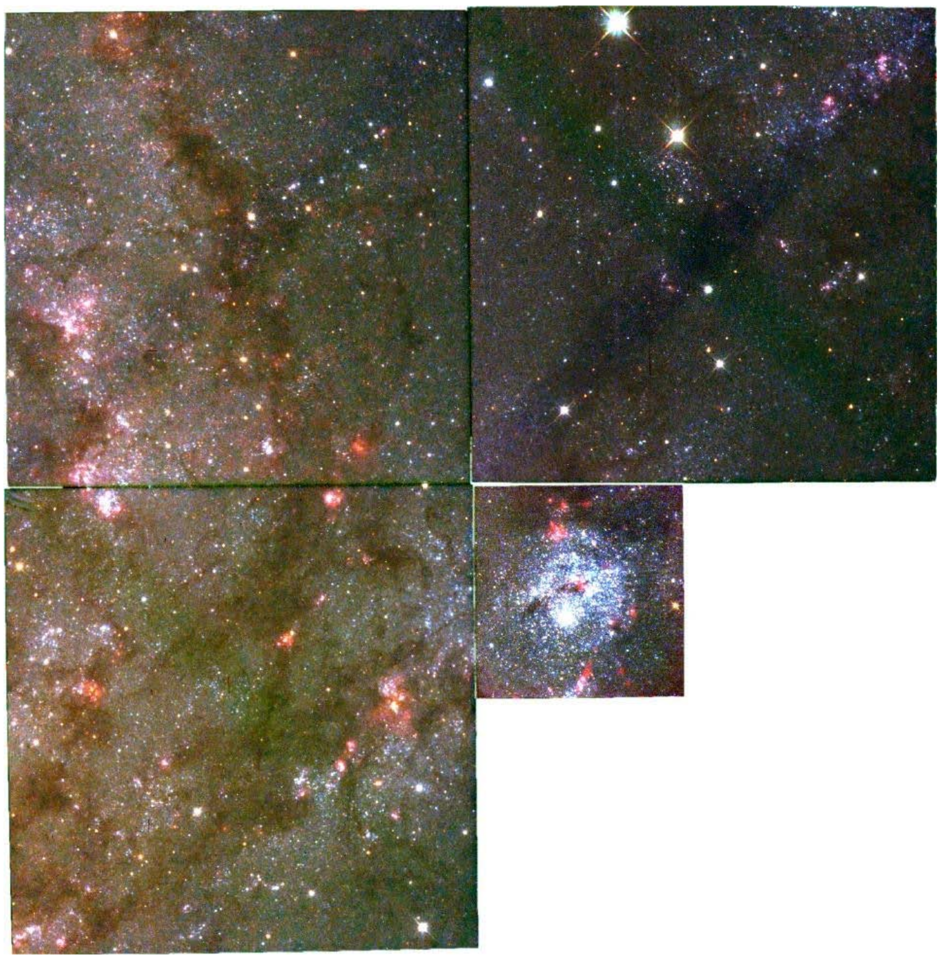

Figure 4: South-West region of the galaxy NGC 6946 showing the stellar complex. North is at top and East on the left.

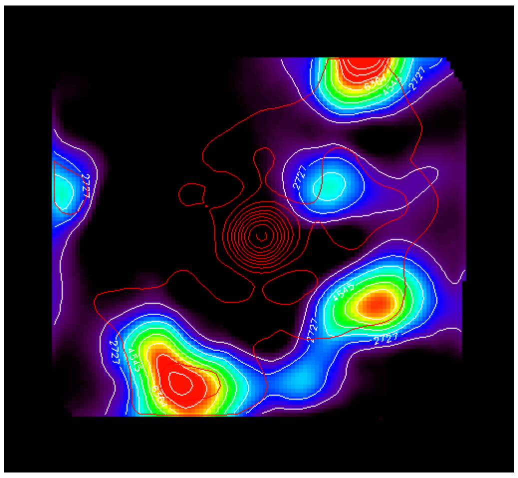

Figure 5: Hα map of the complex. Contours in the V band are overprinted on the map indicating the position of the SMYC. The map is 32 arcsec wide. North is at top and East on the left.

Hα is lower than 5, or when the standard deviation of the mean velocity is larger than 20 km s^{-1}, the fiber is discarded. The fibers span a velocity range from 90 to 190 km s^{-1}. The radial velocity expected from a pure rotational model of the galaxy is between 120 and 140 km s^{-1} for this region.

The main feature that can be observed in this map is the presence of a RV gradient, about 10 arsec in spatial extent and 100 km s^{-1} in velocity, close to the SMYC. This gradient is located in the border where the S/N ratio is lower than 5 and where the emission in Hα is very weak.

From the quotient between Hα and Hβ we have derived the extinction map. As in the radial velocity map, only those fibers with a S/N ratio of the line quotient greater than 5 were used (Figure 7). The quotient has been tied to the absorption in the B band, so that it can be compared with the extinction map derived from the UBV photometry of the stellar component [27]. There is a good agreement between the extinction derived from the gas and that from the stellar content, at least for those regions where the Hα / Hβ quotient could be estimated in a reliable way.

Pursuing the aim of finding the possible origin of this complex, we need to know better the physical processes which drive the current excitation of the gas.

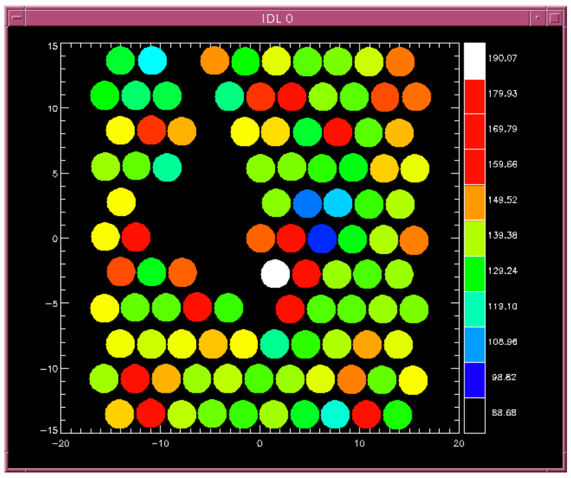

Figure 6: RV map of the complex where the location and arrangement of the INTEGRAL fibers is shown. Dark regions correspond to the area where the emission in Hα was so weak that the S/N ratio was below 5. The orientation is the same as in Figure 5.

Thus, we need to know whether the ionization state has been originated by high energetic photons or by shocks.

The analysis of several diagnostic tests shows that the ionization of the external semi-ring of Hα observed in Figure 5 seems to be originated by energetic photons rather than by shocks. However, in the area close to the RV gradient, the sulphur emission could suggest the signature of shocks.

All these features suggest that the Hodge complex is very similar to any other HII region, although it works at larger scale. The possible origin of the complex, as well as of the SMYC, is still a matter of debate and we cannot offer a definitive scenario yet.

4.2 The Local System

Our Sun is placed close to the intersection of two stellar systems tilted with respect to each other around 20 degrees: the local Galactic disk and the Gould Belt (LGD and GB hereinafter). While the LGD contains stars of any age, according to the history of the star formation in this location of the Galactic disk, the upper age limit for the stellar component of the GB is 90 Myr. The GB system

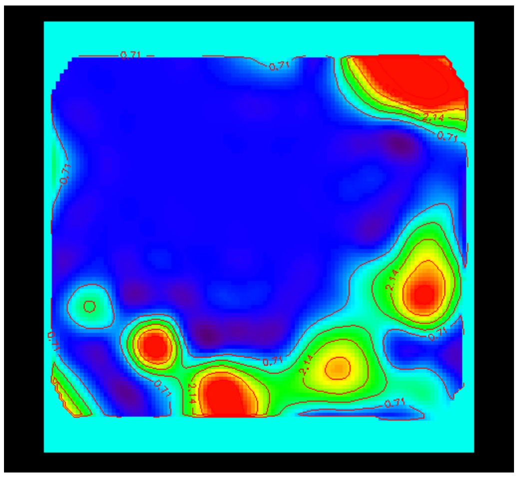

Figure 7: Extinction map derived from the Hα to Hβ ratio in B magnitude.

contains many of the nearby OB associations, many young low-mass stars which are bright in X-rays, and much interstellar atomic and molecular gas. Its total stellar mass has been estimated as a few times 10^5 solar masses (see [30, 24, 25] for extended reviews). According to these data the GB can be envisaged as a typical star complex, so an understanding of this system would be helpful in the detection of comparable systems at larger distances [31, 10].

But, is the Gould Belt a real star complex?

The physical properties of the GB, summarized above, seem to indicate that we are facing a true star complex. On the other hand, there are other observational facts that can be interpreted as evidence that the Gould Belt is not a complex born from a monoparental cloud, but instead a mere spatial coincidence of several moving groups which were generated at different places and, possibly, at different times.

The analysis of the residual velocities for the stellar component of the GB yields a very negative vertex deviation ($l_v \approx -50^o$) [32]. These authors demonstrated that any model for the formation of the GB, either from a single explosion or from multiple (synchronized or not) explosive events, could not explain the observed kinematics of the stellar component and the vertex deviation of the residual velocities. Even if the origin of the GB is sought in the collision of a HVC

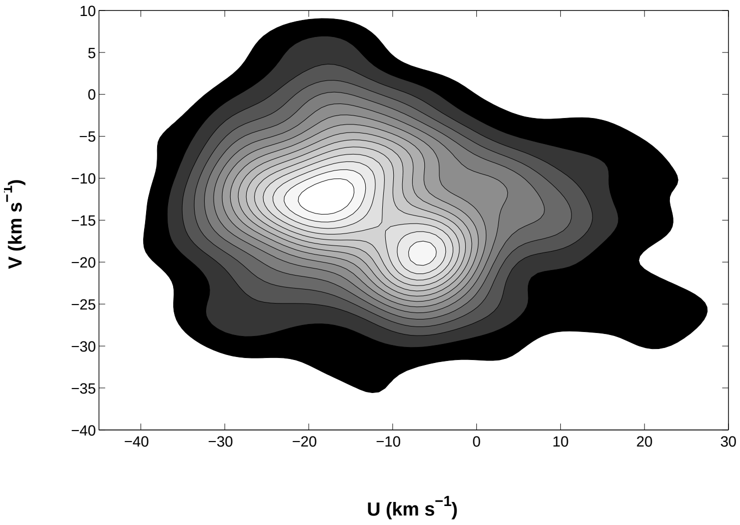

Figure 8: Density map of the GB velocity field (U goes in the direction of the Galactic center, V in the direction of Galactic rotation) showing how it is dominated by two moving groups. Reprinted from [34], with permission.

with the Galactic disk [33], the vertex deviation of the resulting stellar velocity field is always positive, and does not fit the observed one for any impact angle, kinetic energy of the shock or evolution time. The Galactic gravitational potential dominates over the initial conditions in less than 3 Myr.

Moreover, the distribution of the residual velocities of the GB stars can be described in terms of two moving groups, the Pleiades and IC 2391 ([32, 34]; see Figure 8). If the Pleiades moving group is eliminated from a sample of GB stars, the remaining ones show a positive vertex deviation that matches the value expected from a dynamical analysis [32]. Similarly, [34] demonstrate that if the GB is eliminated from a sample of OB stars of the solar neighborhood, the remaining LGD also shows a positive vertex deviation close to 20 degrees. Thus, the vertex deviation and other kinematic characteristics of the GB could be explained by the relative position of two moving groups in the velocity space. This would lead to tackle the issue of the origin of the GB via the origin of the moving groups and their evolution until their present relative position in the velocity space.

We must bear in mind that the Pleiades moving group shows a wide range of ages, from the 80 Myr of the Pleiades cluster to the 1 Gyr of the giant stars that belong to the moving group [35]. Thus, it does not seem as if we should consider the superclusters as the progenitors of the moving groups, but as "dynamical traps" originated by the inhomogeneities in the Galactic potential. Then the two moving groups that seem to form the GB do not necessarily share a common origin. Since the GB was discovered by its relative position in respect to the plane of the Milky Way [36], it should be asked if this inclined structure may be simply a chance superposition of two dynamical streams generated by the perturbations of the Galactic potential. Thus, the spatial coherence observed in the GB may be just a transitory state and not the signature of a true star complex.

Obviously, we do not have any picture of the GB taken from another galaxy, but we can simulate the aspect that it would have seen from outside the Milky Way. If it resembles that of other star forming regions in external galaxies, the question of whether they were born from a single parent cloud or they are just the spurious projections of smaller regions under inhomogeneous potentials becomes relevant.

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