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STELLAR COMPLEXES IN NEARBY GALAXIES

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Abstract. The set of physical processes that we call star formation occur at different spatial scales and along the whole life of the galaxies. Stellar complexes (with sizes between 300-1000 pc) represent the highest hierarchy of coherent star formation in galaxies. They turn out to be formed by associations, clusters, etc, in a cascade of sizes, still containing, in some cases, large gas reservoirs. The history of the star formation within the complex, its content of gas, ionization diagnostic diagrams, internal kinematics, and age spatial patterns are crucial data for understanding how the star formation started in these big clouds and how evolved and propagate along the complexes. In this talk, I will discuss the main guidelines of our project to study the star formation processes at large scale and will show the results derived from the study of a big complex in NGC6946.

1. INTRODUCTION

Star complexes are the largest region of coherent star formation in galaxies. The history of the development of this concept, as well as its classification and nomenclature can be seen in Efremov (1995), Elmegreen and Efremov (1996) and Elmegreen (2006) and we refer the reader to these papers for a comprehensive study.

Star Complexes represent the largest level in the hierarchy of star forming regions in galaxies and, depending on the main properties of the host galaxy and, on how the star formation proceeded on it, we can differentiate several morphologies in these structures. But in general they include associations of Cepheid stars (Efremov, 1978), red supergiants, WR stars (Alfaro et al., 1992a), young clusters (Alfaro et al., 1991), OB associations (Ivanov, 2004) and HII regions.

In this contribution, we would like to focus on their spatial and kinematic distribution in the host galaxy and, on the multi-wavelength study of some peculiar complexes.

2. SPATIAL STRUCTURE AND STAR FORMATION

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 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 (Alfaro et al., 1991; see Fig. 1 in that paper). A very striking feature appearing in this map was a large (≈ 3 kpc along the major axis) and deep depression (Z≈ -150 pc) located in the third galactic quadrant, we called "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 Efremov (1978) 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 (Alfaro et al., 1992b). Similar results were found by Berdnikov and Efremov (1993) from the analysis of the spatial distribution of Cepheid stars. All these results led us to propose:

- 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, as the HVC-disk collisions are, which could explain the formation of structures 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. KINETIC STRUCTURE

Many different physical processes have been proposed as the driving forces for these corrugations (see Alfaro, 2003); 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 disposal a very good discriminatory tool. If you look back into the literature searching for vertical velocity fields in galaxies, you find nothing, excepting some recent studies by Fridman et al. (2005), in other galaxies, and Fresneau et al. (2005) in the Milky Way. Why this lack of information?

Roberts (1969) showed that the encounter between a density way and the gas disk could generate vertical motions with amplitudes always lower than 3 km/s.

This caused that, *when HI observations of face-on galaxies showed extended velocity components with dispersions of the order of 20 km/s, they were attributed to* *other phenomena, such us galactic fountains, a warping of the HI disk, or intermediate-velocity clouds*, in words of Gómez and Cox (2002).

The results by Roberts are correct, but when you are working with a very thin disk. If, on the contrary, you include a thicker disk, with a scale height of the order of 1 kpc, you find that coherent motions, with amplitudes larger than 20 km/s do appear. And the only ingredient you need for having so thick disk is a magnetic field 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 (Alfaro et al., 2001). We found a corrugated pattern that fitted very well the prediction of the models by Cox's team.

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. Otherwise the hypothesis of a magnetized disk was becoming more fruitful time to time. A Korean group in collaboration with the Mexican team of UNAM took the problem of Parker instability again, but now working with more realistic assumptions about the magnetic properties of the gas (e.g. Franco et al., 2002). The results were very promising:

- The Parker instability in a magnetized spiral arm arranges the gas forming clouds, 10^7 solar masses in mass and 1 kpc in size, 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.
- The model also predicts a vertical velocity pattern along the spiral arm.

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

- The hypothesis of a magnetized disk makes easier the agreement of corrugation models with observations.
- 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: certainly prove the existence of velocity corrugations in the disk of face-on galaxies. This project must be accompanied with the development of several improvements in the model codes.

4. MULTI-WAVELENGTH ANALYSIS OF PECULIAR STAR COMPLEXES

Other way to aboard the study of the origin and evolution of the star complexes is to analyze the nearby complexes in great detail. Why we should study these sorts of objects? The analysis of the stellar component and the physical conditions of the remnant gas for this kind of star formation regions could shed light about:

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

To this aim a multi-component and multi-wavelength study of some peculiar complexes has been started. In fact, only two stellar complexes have been so extensively studied: The Gould Belt, our stellar system, in the Milky Way (see Grenier, 2004; Elías et al., 2006), and other harbored by the galaxy NGC 6946. We shall focus our attention on the stellar complex in NGC 6946 which has been analyzed from several points of views and at different wavelengths in the last years.

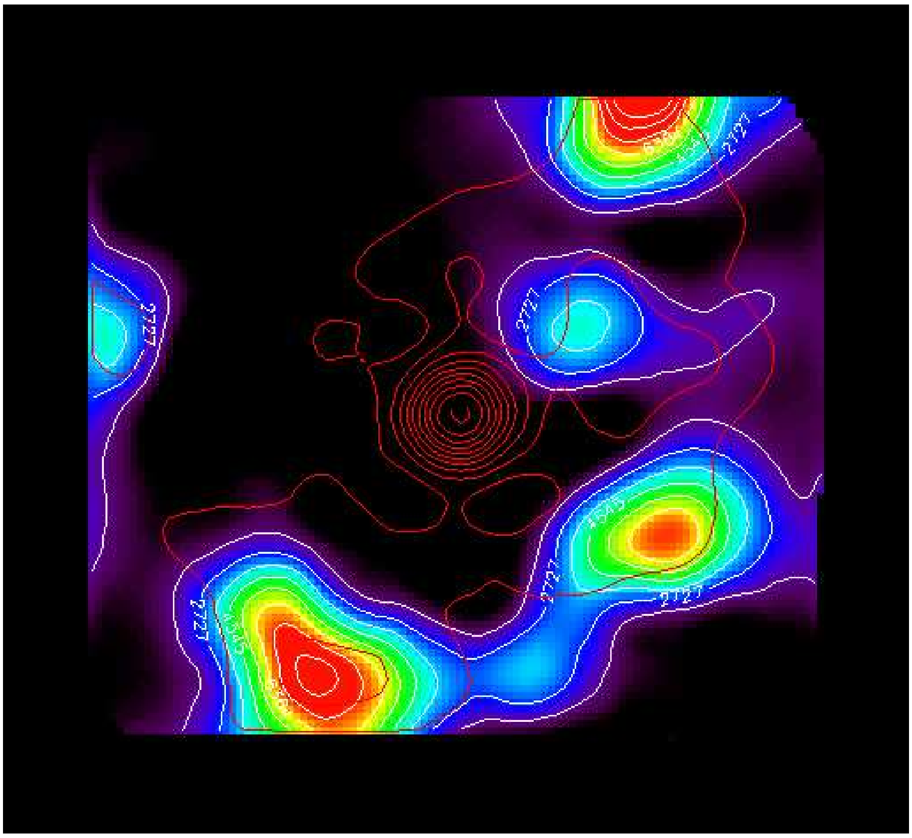

Figure 1: Hα map of the complex. Contours in V band are overprinted in the map indicating the position of the SMYC.Map is 32 arsec wide. North is at top and East on the left.

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 over the entire disk.
- Also 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).
- It is the galaxy with the highest number of observed SNs (8).
- Many very massive and energetic High Velocity Clouds (HVCs) have been detected and associated to this galaxy.
- Two dwarf galaxies seem to be orbiting around it. A weak bridge of HI, starting at the outer disk and directed toward the projected position of the two satellites, could suggest that a third neighbor has merged with the main body.

But, the 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 Paul Hodge (1967) and re-discovered by Larsen and Richtler (1999) thirty years later.

4. 2. THE COMPLEX

The complex is 600 pc in diameter and is placed about 5 kpc to the south-west of the galaxy center. 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 (one million of solar masses and about 15 My old) (Elmegreen et al., 1999; Larsen and Richtler, 1999).

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 (Larsen et al., 2002).

Different groups of ages present different locations inside the complex. Supergiants (25 My old) shows to be concentrated toward the center of the object, close to the SMYC, while the youngest OB stars form an arc shaped structure to the NW of the central cluster (see Fig. N) (Larsen et al., 2002).

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 (Efremov et al., 2002).

4. 3. 3D SPECTROSCOPY

New observations have been obtained, mainly addressed to get more information about the physical properties of the ionized gas. In August 2003, 3D spectroscopy of the complex was taken with the 6m telescope at SAO (Russia) and the Williams Herschel Telescope (WHT) at Roque de los Muchachos Observatory in Spain. The preliminary analysis of the INTEGRAL data, 30 arcsec by size centered at the SMYC, taken with the WHT yields the following results.

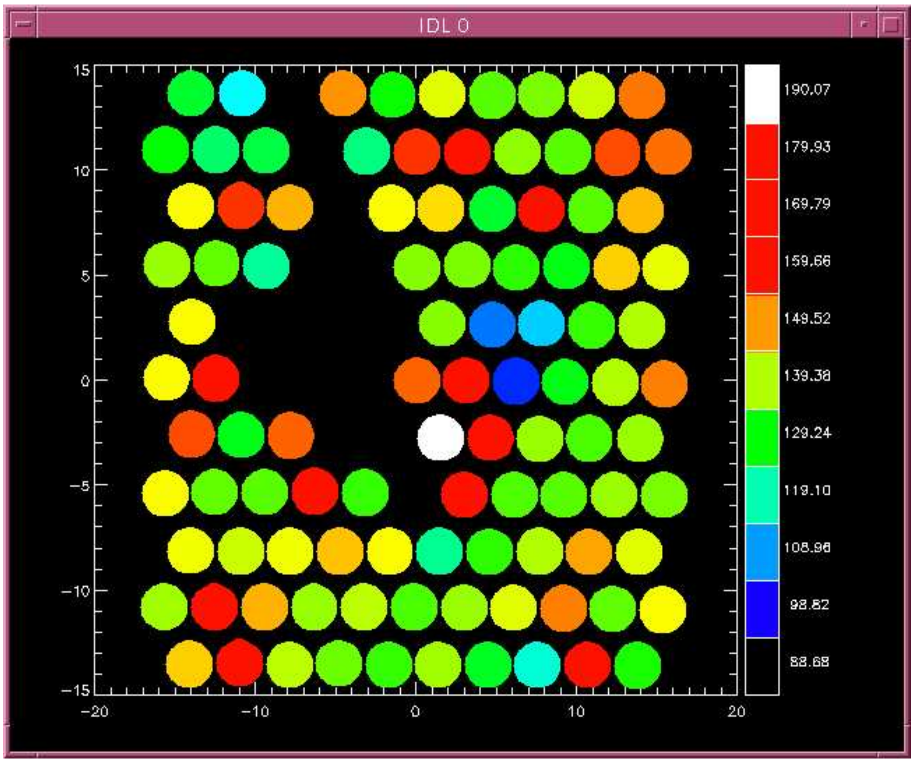

Figure 2: Radial Velocity map of the complex where the location and arrangement of the INTEGRAL fibbers is shown. Dark region corresponds to the area where the emission in Hα was so weak that the S/N ratio was below 5. Orientation as in Fig. 1.

The Hα map (see Fig. 1) displays a drastic contrast between the emission coming from the outer ring and those generated in the NE side of the complex. Thus, the Hα image shows an almost circular shell in emission, surrounding the stellar component.

In Fig. 2 we show the distribution of the fibbers and, in a color code, the mean velocity per fibber, estimated as the average of the RV for three different emission lines. When the S/N ratio of Hα is lower than 5, or when the standard deviation of the mean velocity is larger than 20 km/s, the fibber is discarded. The fibbers span a velocity range between 90 and 190 km/s. The radial velocity expected from a pure rotational model of the galaxy is between 120 and 140 km/s for this region.

The main feature appearing in this map is the presence of a RV gradient, about ten arsec in spatial extent, and 100 km/s 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

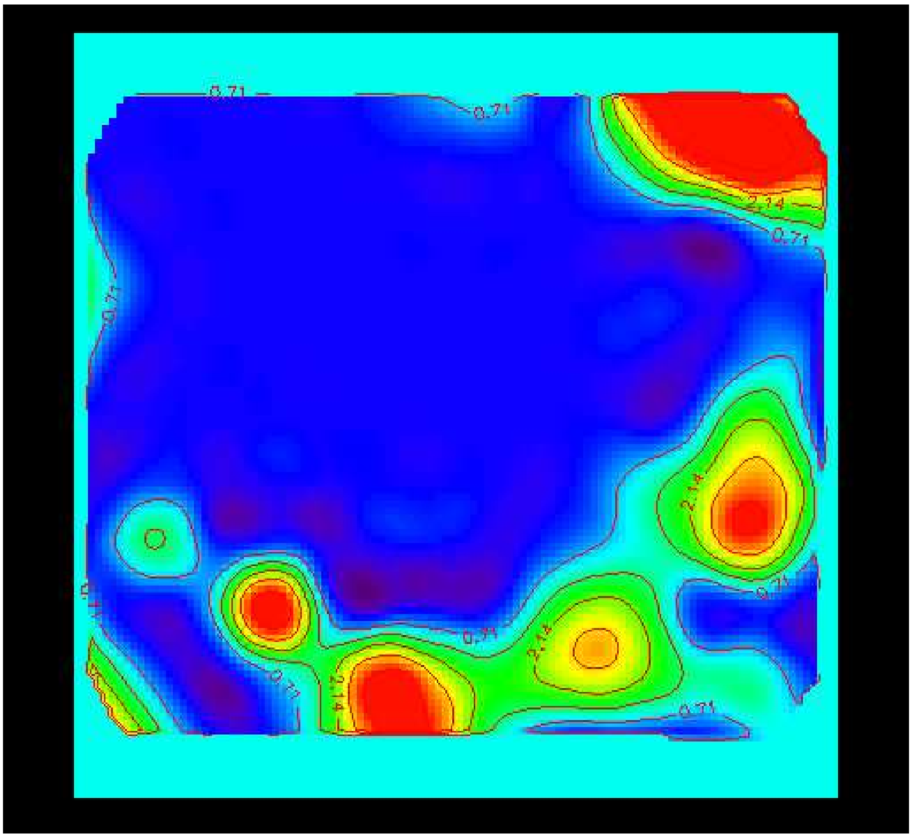

Figure 3: Extinction map derived from the Hα to Hβ ratio in B magnitudes.

in the radial velocity map , only those fibbers with S/N ratio of the line quotient greater than 5 were used. The quotient has been tied to absorption in B band, to be compared with the extinction map derived from the UBV photometry of the stellar component (Larsen et al., 2002). There is a good agreement between the extinction derived from the gas and from the stellar content, at least for those regions where the Hα / Hβ quotient could be estimated in a reliable way.

With the aim to seek for the possible origin of this complex we need better know the physical processes which driven the current excitation of the gas. Thus, we would 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 Fig. 1 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 but working at larger scale. The possible origin of the complex, as well as the SMYC, is still matter of debate and we can not give a definitive scenario yet.

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