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The connection of triggered star formation with the large- and small-scale structure of the interstellar medium

Extracted results of the PhD Thesis

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Budapest, 2007
Introduction

The large-scale structure of the cold interstellar matter in the Galaxy can be significantly affected by violent events. Massive stars can affect the nearby interstellar medium (ISM) not only at late stages when they become supernovae but during more stable states by their strong stellar winds. These processes can create large bubbles in galaxies, built up by shock waves sweeping up gas and dust in thin shells (e.g., Heiles, 1980; 1984; 1990). There is a large number of cavity- and shell-like structures even at high Galactic latitudes, created by the turbulent motion of the ISM, which are apparently similar to the traces of violent events. In the surroundings of the Galactic midplane the shells, compressed by supernova- and stellar shock waves, provide a nest for the next generation of stars. Then high-mass stars, forming here, are the next sources of various shock waves ("propagating star formation"; Öpik, 1953). In the shells of the bubbles, dense cores, being formed within the cloud cores are the first phases of star formation. These cores can be traced by radio observations e.g., at CO and CS wavelengths, and the densest cores at ammonia wavelengths. Afterwards, intensive infrared radiation accompanies the life of young stellar objects; from the cloud core phase to debris discs around the evolved stars.

In my dissertation, I performed a survey of loop-/arc-like intensity enhancements in the diffuse far-infrared emission in the Galactic coordinate intervals: $-90^\circ \leq b \leq 90^\circ$ and $0^\circ \leq l \leq 90^\circ$, $180^\circ \leq l \leq 360^\circ$ (see part studies: Könyves, 2001; Könyves et al., 2002; Könyves et al., 2004a). Merged with the results of the 2nd Galactic quadrant (Kiss Cs. et al., 2004; KMT04), altogether we identified and catalogued 462 of these features. This data forms the Catalogue of Far-Infrared Loops in the Galaxy. Physical and statistical investigations of the objects in our database provides a great opportunity to study the large-scale structure of the ISM in the Galactic neighbourhood of the Sun.

Furthermore, I studied the properties of the LDN 1188 dark cloud and the physical parameters of the star forming dense cores sitting within the cloud, based on infrared, submm and radio observations. LDN 1188 is located at a distance of $\sim 910$ pc (Ábrahám et al., 1995) in the wall of the Cepheus bubble (Kun et al., 1987; Ábrahám et al., 2000), named GIRL G102+06 in our catalogue. From the observational data, we can see that different stages of star formation exist parallelly in the LDN 1188 molecular cloud, from the ammonia cores to the evolved young stars with protoplanetary discs.
Methods

In the first phase of my work shell- and arc-like structures showing an excess far-infrared intensity were identified by eye on ISSA maps (IRAS Sky Survey Atlas, Wheelock et al., 1994) with the help of the SkyView image displayer software (IPAC, Infrared Processing and Analysis Center, CALTECH). Afterwards, for determining the physical parameters of the loops, carrying out statistical analysis and for processing star formation related data I used IDL (Interactive Data Language) routines. Galactic interstellar models (eg. Nakanishi & Sofue, 2003; Ferrière, 1998) or statistical tests (eg. Kolmogorov-Smirnov test, cluster-analysis) could be easily built into my IDL programs.

For the investigation of young stellar objects in the cloud LDN 1188, evaluation softwares, most appropriate ones for a given data-field and generally written to that specific observing device, were used in the submillimeter-, radio-, and infrared wavelength range.

Summary of the results

1. 60 and 100$\mu$m ISSA plates (IRAS Sky Survey Atlas, Wheelock et al., 1994) were used to explore the distribution of dust emission by searching for loop-, and arc-like intensity enhancements. The quest, by eye, for the far-infrared loop features was carried out in the $1^\circ \leq D \leq 40^\circ$ diameter range based on the definition by Tóth et al (1996). Reprocessed IRAS 100$\mu$m and reddening maps by Schlegel et al. (1998) were investigated as well. Geometric parameters of a loop candidate were given by the parameters of its fitted ellipse.

2. In our all-sky survey, 462 FIR loops have been identified. Chronologically, the catalogue of the 2nd Galactic quadrant (90$^\circ \leq l \leq 180^\circ$) was presented by Kiss Cs. et al (2004), where they found 145 GIRLs (Galactic InfraRed Loops). Extending the work to the 1st, 3rd, and 4th Galactic quadrants, then deriving the physical parameters of the loops was carried out by Könyves et al. (2006). The electronic version of the all-sky catalogue with additional data products can be found at: http://kisag.konkoly.hu/CFIRLG. The catalogue contains the name of the loop; the central Galactic coordinates; size, and position angle of the fitted ellipse; and other parameters describing the appearance of the loop in far-infrared images.

3. Using the all-sky sample one of the aims was to analyze statistically the physical properties of the shells. Our loops are real features, material condensations of the
interstellar medium, as their significance analysis showed us. In the size distribution of the shells a trend can be seen that the same amount of energy injection of an event creates larger shells further from the Galactic plane. Furthermore, color indices of the loop walls derived from the 60 and 100 µm radially averaged surface brightness profiles show that most of the shells have a far-infrared colour similar to that of the extended Galactic background emission or Galactic cirrus (Low et al., 1984) with an average value of $\Delta I_{60}/\Delta I_{100} = 0.25 \pm 0.12$ (Lagache et al., 1998), while shells sitting in the Galactic midplane seem to be "warmer".

4. The celestial distribution of the identified loops is rather complex. Loop structures are associated with large-scale molecular material, i.e., in some cases groups of loop centers coincide well with the location of molecular complexes. Galactic longitude distribution of the GIRLs partly reflect the spiral structure of the Galaxy. However, their Galactic latitude distribution clearly suggests that there is an efficient process that can generate loop-like features at high Galactic latitudes. Excluding supernova-explosions and stellar winds of massive stars as dominant effects near the Galactic plane, this should be supersonic turbulence, which governs the structure of the ISM above the Galactic plane.

5. To a subsample of 43 loops of our catalogue, among the ones I found in the 1st, 3rd, and 4th Galactic quadrants, I was able to derive distances using the distances of "associated objects". Together with the 30-loop sample in KMT04 we have a sample of 73 loops with known distances. We used this sample to characterize the large-scale distribution of the ISM in the vicinity of the Solar System. After checking these distances and the distance of the wall of the Local Bubble in the direction of a specific loop using the maps and data based on the measurements of the NaI D-line doublet by Lallement et al. (2003), I got the reassuring result that all of these loops were in or behind the wall.

6. Structures produced by various processes are often characterized by the power-law parameter $\beta$ (e.g., in Oey & Clarke, 1997) of the mechanical luminosity distribution of bubbles or holes. With a specific model this can be converted into a parameter describing the size distribution ($s$) of these structures, then $\beta$ can be determined even for a medium with no stellar energy injection (e.g., a structure created by supersonic turbulence).

I derived these parameters ($\beta$ and $s$), characterizing the structure of the interstellar medium, to the whole sky sample at low Galactic latitudes, where they were
possible to be determined. In a simple model, however, we tested/compared the apparent size distribution with different $\beta$ values. With this test, the structure of the ISM at higher Galactic latitudes could be investigated as well. A study of the cavity size distribution for different parts of the Galaxy has shown that the structure of the ISM at low Galactic latitudes can be explained by high pressure events (e.g., supernovae, stellar winds); while the apparent size distribution of holes favours a fractal structure at high latitudes, similar to what can be created by supersonic turbulence. This is the first study, where the existence of the predicted size distribution of the supersonic turbulence could be proved from real observations.

7. The hot gas volume filling factor $f$ of a galaxy is also an important parameter in characterizing the structure and life cycle of the interstellar medium. Although there are several estimates of $f$ based on theoretical considerations and semi-empirical models, it is hardly constrained observationally to our Galaxy. From far-infrared observations I determined estimates for the hot gas volume filling factor of the the inner ($f_{\text{in}}$) and outer ($f_{\text{out}}$) Galactic environment of the Solar System. The obtained $f_{\text{in}}$ value is of the order of $\sim 20\%$, as predicted by Ferriére (1998) and Gazol-Patiño & Passot (1999). On the other hand, the $f_{\text{out}}$ value is very similar to $f_{\text{HI}} \approx 5\%$ found by Ehlerová and Palouš (2005) through an automated identification of HI shells in the 2$^{\text{nd}}$ Galactic quadrant.

8. I was searching for cloud cores in the LDN 1188 molecular cloud using NH$_3$ (1,1) and (2,2) molecular lines, by processing the up-to-now unpublished observations of the Effelsberg 100 m radio telescope from 1995. Data reduction of the NH$_3$ data was carried out by the CLASS$^1$ software. Based on the measurements, three ammonia cores, with a few arcminutes in diameters, could be identified at the following Galactic positions: [105,96, +4,13], [105,81, +4,20] and [105,98, +3,93]. In two cases the quality of the line profiles of ammonia (1,1) and (2,2) made me possible to derive kinetic temperatures ($T_{\text{kin}} \approx 14$ K).

9. For the mm-radio observations of the LDN 1188 molecular cloud we used the Onsala Space Observatory (OSO) 20 m telescope over two observational sessions in 2004 and 2005. In April/May 2004 I made CS(2-1) maps of the NH$_3$ detected cores. Additionally, I made several pointing observations towards the peaks of the CS maps in HCO$^+$(1-0). More CS(2-1) and new CS(1-0) observations were done in July 2005. The determinations of the physical properties of the molecular cores

$^1$http://www.iram.fr/IRAMFR/GILDAS/
– kinetic temperature, density, mass, etc. – were carried out with the help of the RADEX code (Jansen et al., 1994; Schöier et al., 2005).

10. I established the spectral energy distributions (SEDs) of three young sources in LDN1188 from different wavelength (mainly infrared) observations. From the SEDs I estimated the stellar evolution states of the cores (Könyves et al., 2004b). In this way, two sources (IRS 4 and IRS 6) were qualified as Class I type protostars; and the third (IRS 5) source was found in its earliest phase of stellar evolution (Class 0) based on the definition by André & Montmerle (1994).

11. On December 14, 2003 three infrared sources IRS 4, 5, and 6 were observed with the MAMBO-II bolometer array on the IRAM 30 m telescope in "service mode" at 1.2 mm continuum wavelength. The data were reduced using the MOPSIC package. Due to better spatial resolution at 1.2 mm continuum, comparing to previous infrared measurements we succeeded to resolve the up-to-now compact IRS 4 and IRS 6 into two and three smaller sources, respectively. Their intensities were derived using aperture photometry at 1.2 mm wavelength. In the surroundings of the source IRS 5 only a weak 1.2 mm intensity excess over the background could be observed as an extended emission. In contrast to the results of the infrared measurements with weak spatial resolution, this shows, that IRS 5 is not confirmed as a Class 0 source by submillimeter wavelengths observations.

Future plans

The database of the all-sky far-infrared loops gives us a unique opportunity to study the large-scale structure of the ISM in the neighbourhood of the Solar System. Parameters of theoretically derived Galaxy structure and ISM distribution models were tested with observational data, i.e. with our database, for the first time in the literature.

As one of the continuations of the work, it would be worth studying and comparing the far-infrared structures to features observed at other wavelengths (e.g., certain molecular lines, neutral HI 21 cm radiation, X-rays) of the interstellar medium.

Individual objects of the catalogue are also worth to be investigated in detail, since there is a large number of loops even at low Galactic latitudes, that were unknown before the compilation of the catalogue. These individual studies should cover not only the properties and evolution of the arcs, but the beginning star formation in the loop walls

and the stellar associations, being in different evolutionary states, forming there as well.
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