Galactic champagne **by Francis Boulva**

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Experiment
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Project summary

The main objective of this experiment was to study the interstellar environment of several massive stars. Thanks to an innovative process, we discovered several nebulas surrounding these stars. The study of the morphology and dynamics of these gas structures made it possible to retrace the stars' violent passing.

Project report

Galactic Champagne

Morphology, dynamics and evolution of a cluster of bubbles

Introduction and problem

Wolf-Rayet (WR) stars represent the ultimate stage in the evolution of the most massive stars in our galaxy. They have a tremendous influence on the dynamics and structure of the gas in the Milky Way. The interaction between their powerful winds and the interstellar medium (ISM) results in the formation of huge shells of gas (Weaver 1977). They also heat up the ISM, enriching it with heavy elements, which results in the formation of new generations of stars. The study of WR stars, as well as their surrounding nebulas, is very useful for establishing restrictions on models of stellar evolution. The traditional method of visually detecting bubbles is hindered by the blurring resulting from the accumulation of gas along the sight line, which significantly weakens the contrast.

In 1999, we greatly improved this type of detection through the development of an automated process.[1] This year, we are interested in a cluster of massive stars containing four WR stars. The aim of this experiment is to understand the impact of these stars on their environment and to identify the presence of gas shells associated with these stars in order to determine their intrinsic properties. Our suggested approach is entirely innovative since it involves the use of a software program that we developed.

Working hypothesis

A number of WR stars within our galaxy are surrounded by a neutral hydrogen shell (H_I). Much research (Cappa 1999; Gervais & St-Louis 1999) has shown that they were formed during a phase prior to that of WR (i.e. the *O* phase). Observations reveal that the dynamical age of these structures is far beyond the maximum duration of the WR phase. Studying a region of the galaxy containing this many WRs could help determine whether these stars are just as likely to form this type of shell.

Important concepts

Simplified description of the evolution of massive stars and Wolf-Rayet phases

The evolution of massive stars up to the Wolf-Rayet phase is a function of the initial mass (M_i) of the star, that is, before it loses significant mass. New models (Maeder 1990; Langer 1994) made it possible to identify two possible scenarios: before reaching the WR phase, an *O*-type star becomes either a red supergiant (if $25\ M_{.} < M_i < 40\ M_{.}$, where $M_{.}$ = the mass of the Sun) or a blue giant with variable luminosity, i.e. LBV (if $M_i > 40\ M_{.}$). In either case, the wind characteristics change considerably, modifying the bubble’s structure. The star’s initial mass therefore has a major impact on its environment at the Wolf-Rayet stage.

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[1] This statistical approach, written by Sergey Mashchenko (U. de Montréal) and tested by Francis Boulva, made it possible to discover six gas shells surrounding spectral B-type stars last spring (Boulva 2001).

Structure and evolution of circumstellar bubbles

The structure of these bubbles is characterized by a double shock on the interstellar medium, as well as by a region between the two shocks in which the physical conditions of the gas vary less abruptly (Weaver 1977). To begin with, the star’s wind sweeps the neighbouring gas, creating a cavity where the wind can disperse freely. By hitting the quasi static H_I atoms at high speed, the star’s dense and rapid wind forms a shockwave. The interstellar gas crossed by this shockwave is compressed, forming a shell that can be detected in H_I. Inside this initial shockwave is a second shockwave, resulting from the violent contact between the star’s free wind and the wind already crossed by the first shockwave. The area comprising the wind already crossed by the shockwave and the free-wind region are at temperatures that are too high to be visible in H_I.

The evolution of these bubbles occurs in three phases. The longest phase (~10^6 years)—the only one that interests us in this project—is the one in which the outer shell made up of interstellar matter already crossed by the first shockwave can be observed. The rapid wind responsible for this is slowed by the shock itself and its temperature rises to millions of degrees Kelvin. The strong pressure in this region results in the expansion of bubbles of interstellar matter. The matter that collects behind the first shockwave gradually experiences significant radiative losses and sees its temperature drop from 10^7 K to 10^2 K. Since the pressure remains constant, however, the shell’s volume necessarily decreases. Only then is the bubble visible in H_I, with its sufficiently high density and relatively low temperature.

Innovative computer approach

The automated detection code attempts to detect circumstellar bubbles using the data provided by comparing it with the mathematical model of a spherical, expanding shell. Contrary to the traditional (visual) method, this innovative technique has the definite advantage of being objective. It is also much more sensitive, since it processes all the image's statistical information simultaneously. Using certain parameters (i.e. the object's longitude and latitude, as well as the central star's velocity, the bubble's radius and its expansion velocity), the code is even able to detect bubbles that cannot be detected visually.

Obtaining data and processing images

The radio observations used in this study were obtained with the synthesis telescope at the Dominion Radio Astrophysical Laboratory (DRAO) in Penticton, British-Columbia.[2] The images appear in the form of data cubes, veritable 3-D plates that provide a certain measure of depth and make it possible to visualize the gas structures. The raw radio images are characterized by significant instrumental interference. The pre-processing of the data eliminates most of the undesirable effects. We also used data in 1420 MHz, which should reveal other regions of nebulas observed.

Experimental methodology

Before starting any research on circumstellar bubbles, we had to clearly identify the different WR candidates. An in-depth study of the literature in no way confirmed the existence of H_I shells in the regions studied. A census of the stellar population was needed: aside from the four selected WRs, a cluster of massive stars (*Cyg OB2*) appeared in our images. It should be noted that a very large-scale bubble surrounding two OB associations of the Cygnus constellation (Dewdney & Lozinskaya 1994) had already been detected, a sign of the highly complex dynamics of this region. We then did an initial visual scope of all the radio data (in H_I and 1420 MHz) in order to identify the most apparent structures. Applying the detection code requires that we delimit by *cutting*

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[2] The data is provided by a Canadian consortium of astronomers working on the Canadian Galactic Plane Survey, the aim of which is to take soundings of a good part of the Milky Way in the radio spectrum. The images of the galactic plane are among the sharpest and highest resolution ever obtained in this spectral band (H_I).

tiny cubes centred on each of the stars to be studied; this step is critical in order to limit the duration of the mathematical operations and to use compatible statistical data. Finally, we studied the bubbles found by means of the statistical survey and the visual inspection of the data cube.

Presentation and discussion of results

Discovery of a cluster of circumstellar bubbles

An initial inspection of the H_I radio data made it possible to identify a new cluster of bubbles, probably associated with *Cyg OB2*. This series of shells nested one inside the other was formed either by the overall cluster or by the individuals that make up the cluster. We also discovered a very well-defined ellipsoidal cavity surrounding star WR144. A more in-depth study of this star is presented in the second part of the analysis. Using the automated detection software, it was possible to confirm the existence of the bubble surrounding WR144 and to detect the presence of another H_I shell in the immediate vicinity of two other Wolf-Rayets (WR145 and WR146). In the latter case, the weak contrast and the blurring resulting from the gas made visual detection impossible. The last candidate retained in this experiment is quite unique. The nebula discovered surrounds a very rare and highly complex binary system (Wolf-Rayet – compact companion[3]). We will therefore not dwell on this last observation.

Dynamics and evolution of the WR144 nebula

In response to our initial hypothesis, it is critical to estimate the age of the nebula found around WR144. We therefore determined its expansion velocity, as well as its radius. Its age is estimated to be ~8.5 x 10^5 years. This value is within the time scale of the WR phase (~ 10^6 years), meaning that the bubble was possibly blown, at least in part, during

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[3] In a binary system, two celestial bodies orbit around one another. If one of these bodies collapses, it is referred to as the *compact companion*. In the case of Cygnus X-3, an intense source of X-rays, the object orbiting with the Wolf-Rayet is quite likely a black hole. It is the only known example of this type of binary system.

this stage. If this is the case, it is the very first observed H_I bubble blown by the Wolf-Rayet wind. Other estimates lead us to believe that the Wolf-Rayet's ancestor *O* is primarily responsible for this formation. In order to decide between these two results, we calculated the energy injected into the nebula by the star, which made it possible to obtain the wind force (mechanical luminosity) responsible for the contraction of the H_I gas. By comparing this value with a quantitative reading of massive stars (Howarth & Prinja 1989), we can determine that the bubble was blown by an *O*5 star weighing approximately 60 solar masses. As described previously, this very massive celestial body would have become an LBV star before entering the Wolf-Rayet phase. The LBV phase is extremely short (10^4 years) and barely understood by astronomers, making the study of the WR144 nebulosity even more captivating. In the coming months, we will be doing a study on the mass loss of WR144 and on the chemical composition of its environment. The region's tremendous complexity, however, will likely make such research difficult.

Conclusion and applications

The study of the structure and dynamics of nebulas, veritable stellar archaeology, is a key to understanding the evolution of the most massive stars. This experiment made it possible to better appreciate this very complex region of our galaxy. The statistical analysis of the data cubes made it possible to confirm the presence of the bubbles discovered with greater certainty. This innovative method is in the process of becoming a useful tool for nebula researchers. Such algorithms are often used in medical imaging and visual recognition systems.

[4]Acknowledgments

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[4] I would especially like to thank professor Nicole St-Louis (Université de Montréal) for her help and support during the experimental phase and Dr. Sergey Mashchenko (U de M) for the new version of the automated detection code. This work would not have been possible without them.