The Large Magellanic Cloud as a testbed for the astronomical Virtual Observatory

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ABSTRACT

We are carrying out a comprehensive study of massive star forming complexes in the Large Magellanic Cloud, through the study of ionized regions. Preliminary results for the nebula LHA 120-N 44C are presented here.

We are blending i) the spectral and morphological information contained in images taken through selected filters that probe lines sensitive to factors such as excitation mechanisms or hardness of the ionizing radiation, ii) with the already existing photometry from the 2MASS near–infrared survey and iii) multi–wavelength archived images retrieved from various locations.

The merging of all these sources of informations will allow us to establish a close link between massive stars and the surrounding interstellar medium and should help constraining the local star formation history and dynamical evolution of these ionized regions in the Large Magellanic Cloud. In this respect, the Astrophysical Virtual Observatory (AVO) prototype tool has proven to be a powerful tool to speed up the discovery process.

Keywords: Large Magellanic Cloud, Massive Stars, HII Regions, Star Formation History, AVO Prototype Tool, Virtual Observatory

1. INTRODUCTION

The Astrophysical Virtual Observatory[1] is already keeping its promises as demonstrated at the AVO First Science Demo event held at ESO, January 27–28, 2004. The progress of the AVO project has been presented to the AVO Science Working Group by means of scientific scenarios and the emphasis has been put on scientific capabilities. As a result of this First Light Event, the latest AVO prototype called "Aladin for AVO" has been made available to the astronomical community. Description and hands–on use are available from the AVO website.[2]

It is clearly stated that the Virtual Observatory (VO) is technology enabled but science driven. Thus in this paper we propose to use and contribute to the developments of such VO tools, applied to the general astronomical research fields of stellar population studies and star formation history of nearby galaxies such as the Magellanic Clouds. Feedback from science users of the archives, as we propose to be in this paper, help keeping the development of sophisticated VO software tools very close to the actual science requirements. Furthermore, we are willing to use, spread and promote VO tools among the astronomical community, since it is a major requisite to enable a successful Virtual Observatory. As an example, we plan to make extensive use of the AVO prototype. This prototype is a testbed and demonstrator of new technologies and methodologies.

We intend to carry out a comprehensive study of the present–day massive stellar contents in the Large Magellanic Cloud (LMC), including the youngest generations of massive stars and to establish the energetic budget of such regions. Massive stars are an essential part of the galactic evolution process, though their lifetime (10^7 yr) is negligible at a galactic timescale. Through their stellar winds during lifetime and at death when they explode into supernovae, they release not only a lot of kinetic energy into the interstellar medium but also the heaviest elements of the Galaxy which are created deep in their center, contributing to its enrichment in metallicity. Massive stars are often found in HII regions where they ionize and shape the surrounding gas, creating beautiful star–forming nebulae, as shown in ESO Press Photo 31/03.[3]

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2. SCIENTIFIC RATIONALE

The Magellanic Clouds, and in particular the LMC, have been so far an especially fertile ground with respect to the study of massive stars. Their relative proximity allows a good spatial resolution, their distance is known to a relative accuracy better than for most star forming complexes in our own Galaxy, and the nearly face–on view of the LMC from our vantage point largely removes problems of foreground extinction and of confusion along the line of sight that complicate the study of extended HII regions in our own Galaxy. Moreover, it is generally possible to identify, resolve, and study individually in detail the brightest stars in the different star forming regions, while the difference in metallicity between the LMC and the Milky Way allows an observational assesment on its consequence. Thus, the LMC clearly stands out as a perfect laboratory to build up a small scale Virtual Observatory.

To study the massive star forming complexes of the LMC, our goal is to blend both new observational data with archived data (meaning both catalogues and images):

- The spectral and morphological information contained in new Wide–Field Images taken through selected filters will probe lines sensitive to factors such as excitation mechanisms or hardness of the ionizing radiation to derive fundamental properties of the stellar components.
- Images from surveys carried out in a wide variety of wavelengths are available throughout the worldwide distributed archives. They will provide valuable additionnal strucural informations. Photometric information stored in the derived point source catalogues of those surveys (e.g. 2MASS) will be useful to derive the energetic budget of the stellar populations involved. Note that multi–wavelength cross–identifications for the major sky surveys DENIS, 2MASS, GSC-II and UCAC are already available as part of an accepted Astrovirtel proposal: the Master Catalogue of stars towards the Magellanic Clouds (MC2 – Delmotte et al. 2002,[4] Delmotte et al. 2001[5]).

The merging of all these data will allow us to probe broadly different structures such as giant molecular clouds, diffuse neutral gas, photo– and shock–ionized regions, and supernova– and wind–blown bubbles, all of which are in a way or another related to the formation and the lives of massive stars.

As an example of our work in progress and to emphasize the benefits of the AVO prototype tool, we expect to identify the origin of the excitation of the nebula called LHA 120-N 44C, located on the southern part of the giant bubble DEM L 152 (also called bubble 1), the biggest feature in the LHA 120-N 44 complex. LHA 120-N 44C is one of the six HII regions in the Local Group to generate photons with energy higher than 54 eV, the ionization potential of HeII. This kind of emission is typical of planetary nebulae. But LHA 120-N 44C is too large and luminous to belong to such kind of nebulae. Many hypothesis have been raised (Garnett et al. 1991,[6] 2000[7]). Stasińska et al. (1986)[8] found out a O–type star in the center of the nebula, with an estimated temperature of 70 000 K. However, a spectrum of this particular star has been obtained by Garnett et al. (2000) who conclude that it could not be the one involved in the ionization process (spectral type $\sim$ O7 III-V). Pakull & Motch (1989)[9] are in favour of a fossile nebula explanation, where an X–ray binary would have shut down recently in the 70's.

Nevertheless, the origin of the ionization is still unclear and this is not without any consequences. Indeed, if such sources are relatively common, they could modify on a cosmological scale our spectral interpretation of e.g. far away starburst galaxies. We would like to propose here a new alternative to the study of LHA 120-N 44C and take a step toward solving the origin of this mysterious nebula.

3. COLLECTING DATA

New science is expected to be made possible thanks to the huge potential of scientific discovery through worldwide distributed astronomical data and resources. We will describe here the origin and properties of our data gathered from various locations.

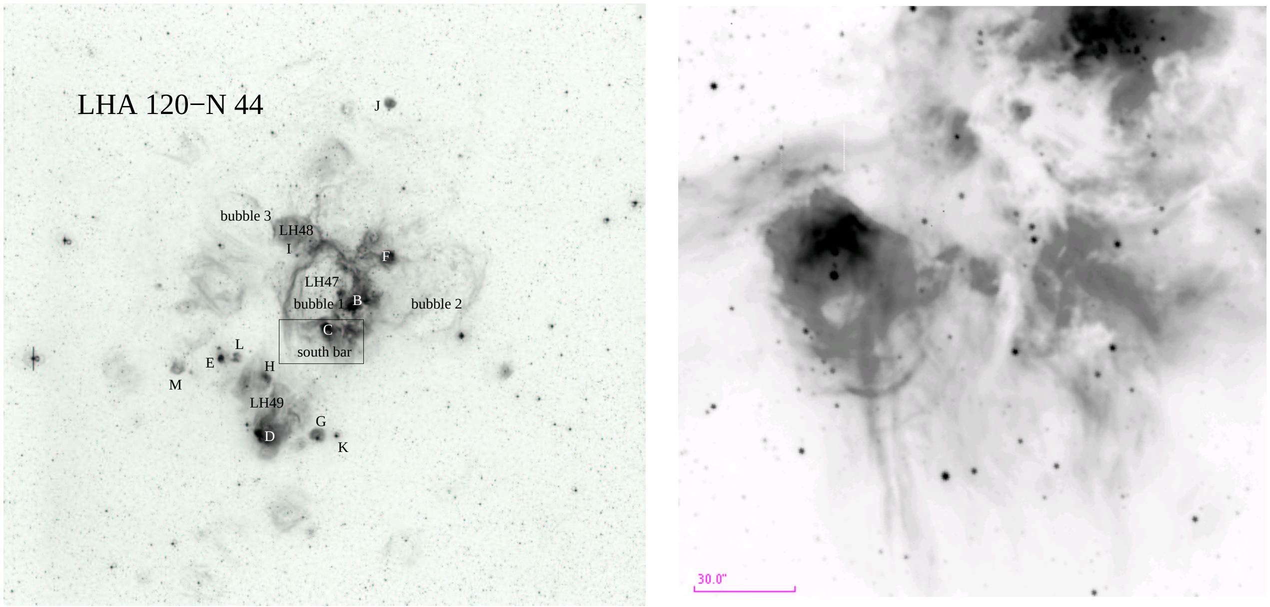

Figure 1. The left picture displays our Hα WFI image of N44, with main nebulosities labelled according to the litterature. LHA 120-N 44C is located below the main central giant bubble. North is up and East is left. Colours are reversed: black corresponds to high pixel values. The right picture is a zoom centered on LHA 120-N 44C.

3.1. Narrow–Band Imaging

In Period 68 of the European Southern Observatory, we obtained time for a pilot study on two regions of the LMC, LHA 120-N 44 and DEM L 299, in the scope of program 68.C-0019(A). We wanted to use the advantages of narrow–band imaging in obtaining both spectral and morphological information to study in detail those large ionized regions in the LMC. Imaging of emission–line regions in selected narrow bands is a powerful way of obtaining simultaneous information on their physical conditions, their excitation mechanisms, and their morphology. In particular, diagnostics based on different emission–line ratios can yield detailed information on the spectral energy distribution of the massive stars ionizing HII regions at wavelengths beyond those accessible to direct observations (e.g. Osterbrock (1989)[10]). Garnett et al. (2000)[7] and Oey et al. (2000)[11] provide two recent and different examples of nebular emission line diagnostics applied to the study of massive stellar populations in LMC star forming regions. Narrow–band images of the N44 nebula were obtained 2001 December 6-7th at the MPG/ESO 2.2 m telescope with the Wide Field Imager (WFI). Images were taken with the Hα, OIII, SII, 485 and U filters. The broad–band U filter has the advantage of containing the [OII] doublet. For each filter, four exposures of 20 minutes were taken, each image slightly offset to fill in physical gaps between the WFI CCDs. The pixel scale is $0''.238$ pixel^{-1}. The field of view is $34' \times 33'$. An astrometric solution for these images was determined with the use of stars in the USNO catalogue. The astrometric accuracy in the optical images presented here is $\sim 1''$. This program has been successful and already shows spectacular results. Emission lines ratios derived from the images provide information on the physical conditions of the ionized gas and the origin of its excitation, separating photoionization–dominated from shock–dominated areas. More details are available in Delmotte (2003).[12]

3.2. Other Images

The Midcourse Space Experiment (MSX) astronomy experiments aimed at a mid–infrared mapping and at surveying the IRAS gaps. The spectral region covered the range from 4.2 to 26 microns, with four bands A, C, D and E (respectively 8.3, 12.1, 14.7, 21.3 microns). The sensitivity in the MSX 8.3 micron band was about four times more sensitive than IRAS. The four band images covering the regions of the sky in the direction of LHA 120-N 44C were retrieved from the NASA/IPAC Infrared Science Archive.

(a) Hα WFI (b) 2MASS K_s–band

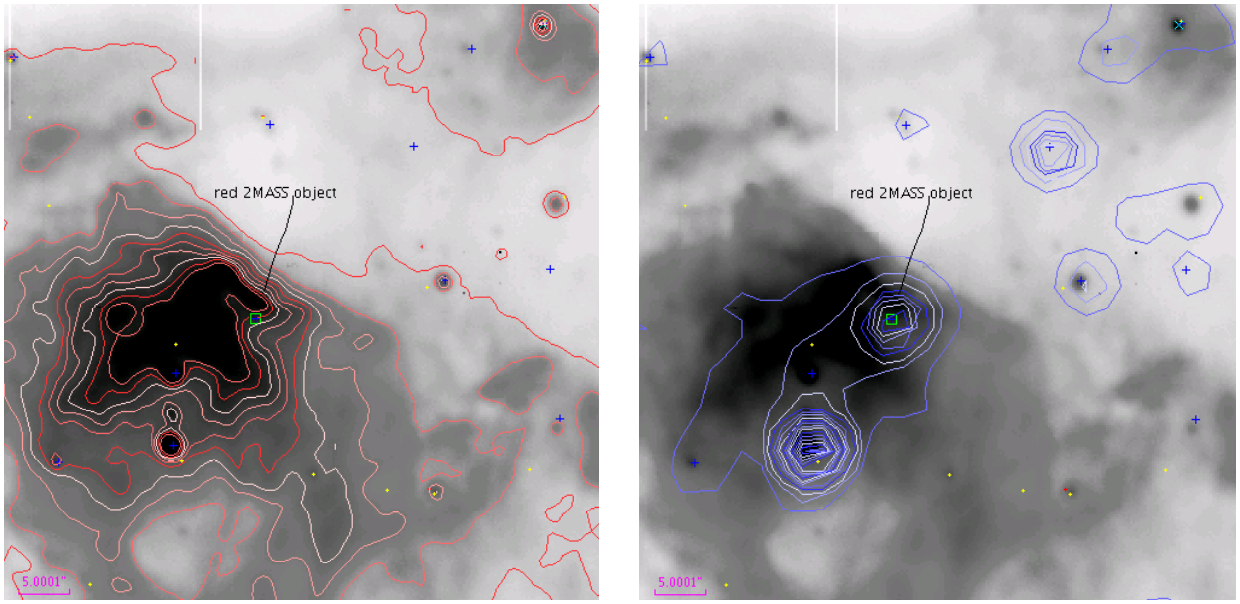

Figure 2. Contour maps superimposed on the WFI Hα image of LHA 120-N 44C. Major differences in the structural informations appear between the visible and infrared images. The pinpointed red 2MASS object is located at the tip of the bright nebulosity on the WFI image. It is highly proeminent at infrared wavelengths and invisible in H_α.

The Sydney University Molonglo Sky Survey (SUMSS[13]) is a deep radio survey of the entire sky south sky, carried out at 843 MHz with the Molonglo Observatory Synthesis Telescope (MOST) with upgraded wide–field capability. This survey consists of about 590 4.3°× 4.3°mosaic images with 45′× 45′cosec δ resolution. FITS mosaics in which selected sources appear are downloaded through a link in the VizieR database at CDS.

3.3. Catalogues

The LMC has been recently fully observed by two major near–infrared surveys: DENIS – IJK_S (Epchtein et al. 1997) and 2MASS – JHK_S (Skrutskie et al. 1997). These surveys provide useful data because of the large number of point sources extracted from the subsequent images, with a spectral energy distribution between 0.8 and 2.2 μm yielding insight on the massive stellar contents of star forming regions in the LMC nearly devoided of two important effects that are a frequent reason for concern at visible wavelengths: the possibility of missing members still embedded in dust, and the contamination of the photometry by bright nebulosity that pervades images at visible wavelengths. Young massive stars are thus easily recognizable in colour–magnitude diagrams using both infrared and optical magnitudes. While the complete census of members and their bolometric luminosities are much better determined from near–infrared photometry, other information is limited as the near–infrared samples the Rayleigh–Jeans tail of the spectral energy distribution of massive hot stars.

4. ANALYSIS WITH THE AVO PROTOTYPE TOOL

To achieve our goals we need using tools capable of integrating all the various heterogeneous data required to solve the mystery of LHA 120-N 44C. Visualization interface of the results as well as interactivity and functionalities such as filtering are also a basic requirement. A fundamental basis for this work is the AVO prototype tool. This prototype is based on the interface of the Aladin[14] interactive sky–atlas developed at CDS, France. Aladin is an interactive software sky atlas allowing the user to visualize digitized images of any part of the sky, to superimpose entries from astronomical catalogues or personal user data files, and to interactively access related data and information from the SIMBAD, NED, VizieR, or other archives for all known objects in the field. Aladin is particularly useful for multi–spectral cross–identifications of astronomical sources and quality control

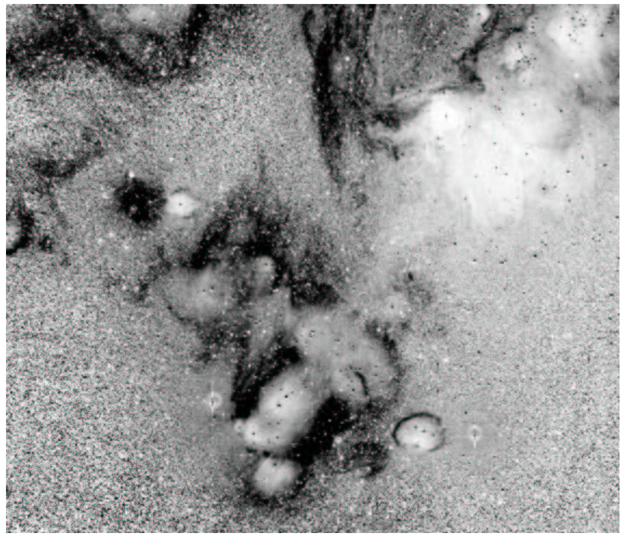

Figure 3. Temperature map of the South part of the LHA 120-N 44 complex, with emphasis on nebulosities D and C. This map is the image ratio [OIII]/[OII]. White means high temperatures. LHA 120-N 44C is far most the hottest extended region.

of new data sets (by comparison with standard catalogues covering the same region of the sky). But the AVO prototype is much more than the Aladin software. New features and new archived data are available. It is a true Virtual Observatory realization and it gives a glimpse of all the future capabilitites that the astronomical community will be provided with.

Here are some of the new functionalities of the AVO Prototype already developed in this respect and with direct relevance to our project: a meta–browser or data–tree to browse the archived data available to the user, the contour functionality of an image as well as RGB combination of several images. A filter functionality allows to i) combine several catalogue parameters with arithmetic operators, ii) set constraints on parameters (or combinations of parameters) to perform filtering and selections, iii) visualize any parameter by changing e.g. the symbols' size. All these attributes can be customized as functions of catalogue parameters (or combination of parameters). Finally, the VOPlot plugin, a 2D data plotter and histogram tool, allows the user to visualize data extracted from any of the catalogues selected. It can be used to display the distribution of any data field, or to plot two data fields against each other. Simple transformations can be applied to the extracted data. The visualized portion can be a dynamically selected subset of point sources overlaid on the images. Some basic statistical information about the selected data can also be obtained. Many other functionnalities of the AVO Protoype exist, though not discussed here. The reader is referred to the AVO TWiki pages for further documentation.

Our new images taken with the WFI show the presence of dust between LHA 120-N 44C and B (see Fig. 1). It is clearly enhanced on Fig. 2(a), where the contour levels are drawn with the AVO Protoype. The infrared 2MASS contour levels are drawn on Fig. 2(b). A first strategy consists now in overlaying on the WFI visible images the catalogues entries from e.g. the near–infrared DENIS catalogue to peer through the dust in the direction of these regions. By comparing their spatial distribution to the temperature distribution (Fig. 3) in the nebula as traced by the [OIII]/[OII] as well as to the distribution of dust, we expect to localize the origin of the excitation. A preliminary inspection already hints at some candidates: inside a $2'$x $2'$ region around the center of LHA 120-N 44C, 13 sources are recorded in the J band, 3 of them also have the $K_{\rm S}$ band (DENIS[15] survey). All these sources are located on the west side of the center of the nebula. In the $4'$ region to the west, we find 19 sources in J and 4 of them are also detected in the $K_{\rm S}$ band. A further step is to look at the physical properties of these objects using 2MASS photometry, which is at least a magnitude deeper than DENIS in $K_{\rm s}$. Thus in Fig. 4 a colour–colour magnitude of all the point sources overlaid around LHA 120-N 44C. The VOPlot[16] plugin

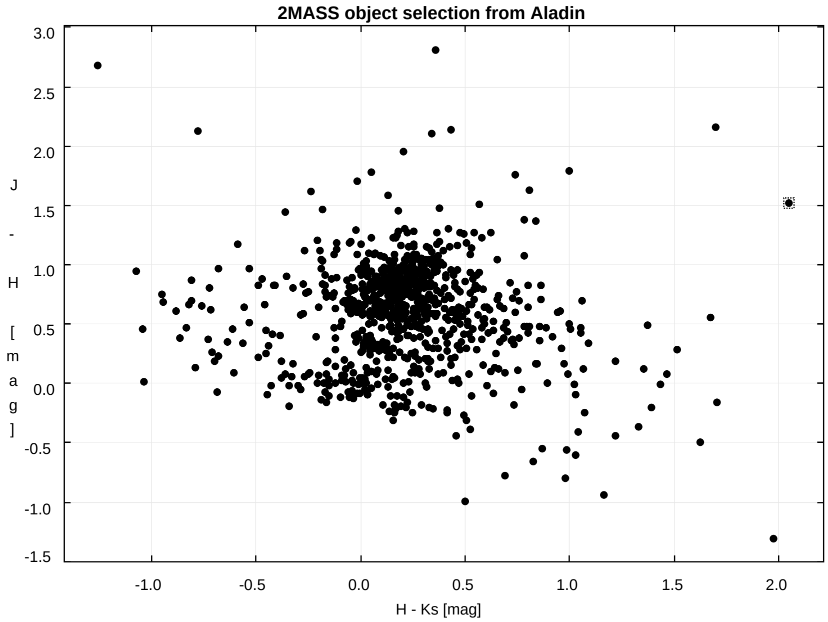

Figure 4. $(J - H,\, H - K_{\rm s})$ 2MASS colour–colour diagram in and around LHA 120-N 44C, obtained with the VOPlot plugin. This tool is highly interactive. It allows the user to identify on the scatter plot some outliers (e.g. the reddest object, outlined here in a square). Once the mouse selected the object, it will automatically blink on the Aladin interface. The reverse is also possible. If a point source overlaid on the image shows remarkable environmental properties, one may want to have a look at its physical properties in the colour–colour magnitude diagram. The source will then be highlighted on the VOPlot diagram.

loads into memory the selected point sources and after manually defining new columns based on the three $JHK_{\rm s}$ magnitudes, namely $(J - H)$ and $(H - K_{\rm s})$, it automatically generates the plot.

As mentionned, a helpful implementation of the AVO Prototype is the ability to display the size of the symbols for catalalogue entries proportional to e.g. the magnitude or the colour. This capability is also much similar to the one provided by the ESO Skycat[17] tool, though the syntax is different and based here on the Unified Content Descriptors (UCDs[18]), some metadata developed at CDS which are of much importance from an interoperability point of view in the context of the VO. Here is the simple piece of code needed to generate a red circle around a point source catalogue entry with a radius proportional to $(J - K_{\rm s})$ 2MASS.

```
# Col.Circle
# This filter draws for each source a circle
# whose radius is proportional to the color
{draw red circle(($[PHOT_JHN_H]-$[PHOT_JHN_K]))}
```

One can in a single glance identify directly on the underlying image some unusual objects. It allows to combine both position and colour information, as seen on Fig. 5. Of course, the next step is to go through the VOPlot plugin to generate global statistics on the coulour–colour diagram and realize that the proeminent object in the 2MASS image has indeed some unusual colour features! This outlier and reddest object on the right of the plot on Fig. 4 lies several sigma away from the global clump of stars.

Further enquiries at other wavelengths with the MSX – Fig. 5(a) – and Molonglo – Fig. 5(b) – surveys around LHA 120-N 44C show interesting features, though not conclusive. The center of the emission at far wavelengths is clearly offset from the visible peak emission.

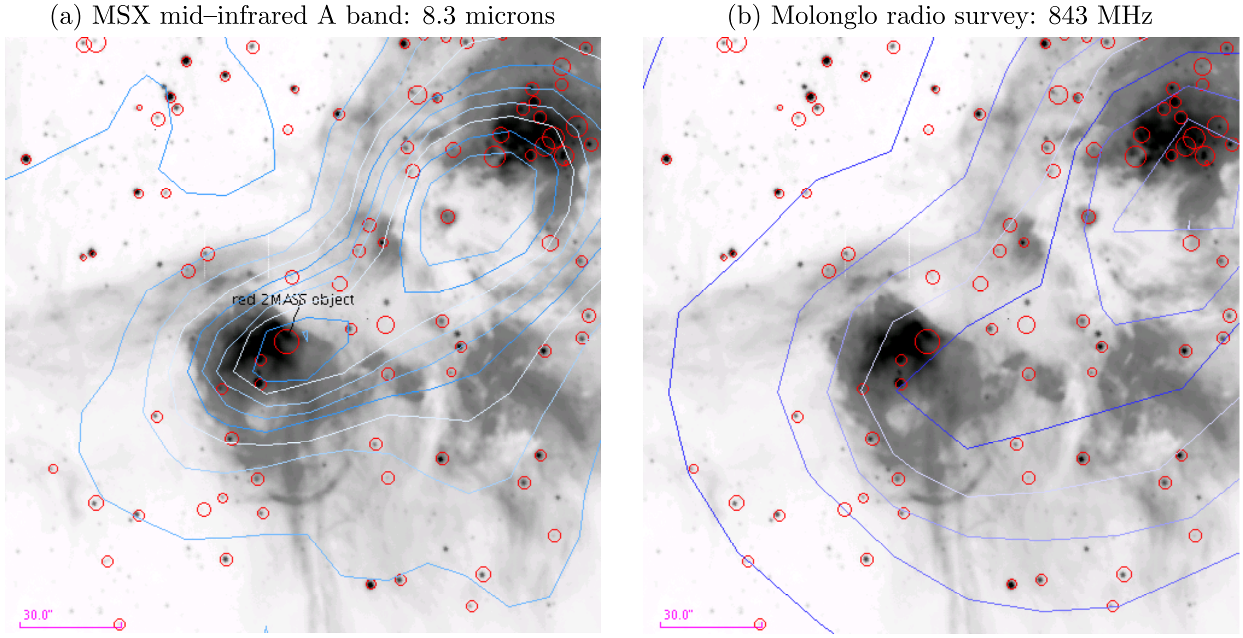

Figure 5. Contour maps superimposed on the WFI Hα image of LHA 120-N 44C. The red circles are proportional to the $(H - K_s)$ colour for the corresponding 2MASS entries. The source labelled `'red 2MASS object'` is far most the reddest one in the vicinity of LHA 120-N 44C.

To conclude regarding the nature of the source at the origin of the LHA 120-N 44C ionized region, we are in favour of a deeply enshrouded infrared object, located in the place of the 2MASS object we identified with outstanding red colours. Thus the ionizing source does not appear to be located within the bright nebulosity. Unlike all previous observational attempts by various authors, the search for a definite indentification and location of the ionizing source should be done instead within the obscured dusty regions. It is probably a young massive star (cluster?). Infrared follow–up spectroscopy of the red 2MASS object could give important clues on the nature of this object. However, obtaining spectroscopy at enough signal–to–noise ratio for classification at infrared wavelengths is a much more demanding task than in the visible (Hanson et al. 1996[19]).

5. CONCLUSION

This study has made use of many archived data. However, the VO era should not lead us to disregard the acquisition of new observational data. Indeed, a fundamental basis for this work has been the narrow–band imaging of the nebulosity LHA 120-N 44C, which offers a much more economical indirect way to probe the principal spectral characteristics of its stars and to identify peculiar members for follow–up that would be unrecognizable from broad–band photometry alone.

Our proposed hypothesis related to the mystery of LHA 120-N 44C has been made possible thanks to the highly interactive and configurable AVO prototype tool. It allows a quick overview of all available data for a specific region on the sky and provide analysis tools to relate heterogeneous data. A major advantage is that each tool is accessible from the same software and fully compliant with each other. It is definitely appropriate to speed up the discovery process and ultimately lead to scientific results.

The ultimate goal of our study of massive star forming complexes in the LMC is to scientifically exploit the potential of a much larger database obtained by the merging of both new observational material and multi–wavelength archive/survey data, covering the whole LMC. These are important issues faced by the Virtual Observatory in its development, with the integration of various heterogeneous data: point source catalogues, images, spectra, radial velocities, variability, etc. Although many detailed studies exist on particular regions of the LMC synthesizing the observations coming from different domains and including the stellar component, comprehensive and comparative studies extended to the whole LMC are still rare. Setting up this large database may allow important progress in this respect by providing a homogeneous massive stellar census with well understood completeness properties all over the LMC.

The Virtual Observatory will be a research area of its own and full of discoveries thanks to frontline technology. However, spreading the knowledge of this newly born Virtual Observatory in the astronomical user community is still of extreme importance. It needs to be done as fast as possible to save time and facilitate the integration of the ever–growing archives inside a VO–compliant global framework. Thus, early science demonstrations of the future capabilities of the Virtual Observatory are a necessity to convince the entire astronomical community of its uttermost relevance.

In this context, the selection of astrophysical objects like LHA 120-N 44C as science cases is a mandatory step to test, validate and exploit those new techniques and tools mentionned above that are part of the cornerstones of a sucessful Virtual Observatory. We hope that it will contribute to its development and help spreading the knowledge of this cutting–edge astronomy, which is being developed in the framework of the International Virtual Observatory Alliance (IVOA[20]). The more rapidly people will get used to the VO concept and tools, the more successful the Virtual Observatory will be.

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