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COMMENTARY "ON TWO H II REGIONS NEAR THE NUCLEUS OF M82" BY RECILLAS-CRUZ & PEIMBERT (1970): THE ARCHETYPE GALAXY OF THE STARBURST PHENOMENA

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RESUMEN

El comentario sobre el artículo "On Two H II Regions Near the Nucleus of M82", por E. Recillas-Cruz y M. Peimbert, 1970, BOTT, 5, 35, 247, revisa el primer intento por explicar el aspecto inusual de las regiones centrales de la galaxia M82. Presentaremos también algunos resultados de estudios más recientes sobre M82.

ABSTRACT

This commentary on the paper "On Two H II Regions Near the Nucleus of M82" by E. Recillas-Cruz and M. Peimbert, 1970, BOTT, 5, 35, 247, will recall the first attempt to explain the unusual nuclear appearance of the extragalactic nuclear regions of the M82 galaxy. We present some comments as well on the many studies that since have been made on M82, the prototype of the "Starburst" phenomena.

Key Words: galaxies: individual (M82) — galaxies: starburst — HII regions

1. INTRODUCTION

The paper by Recillas-Cruz & Peimbert (1970, hereafter R-CP) was a companion of Peimbert & Spinrad's (1970) paper on the physical conditions in the "nucleus" of M82 that brings us back to the dawn of the studies on the evolution of late type-spirals and of galaxies in general. The two M82 papers of that year (Peimbert & Spinrad 1970; Recillas-Cruz & Peimbert 1970; thirty nine years ago!), set the first real attempt to explain the unusual appearance of the extragalactic nuclear H II regions of M82 (NGC 3034) amongst other galaxies and the subsequent investigations on the evolution of irregular and compact galaxies which was to lead to the seminal paper of Lequeux et al. (1979). The nuclear starburst and the associated galactic superwinds along with the filamentary distribution of dust not only give it an appealing morphology but also make it a very interesting object to study in the entire range of the electromagnetic spectrum.

Although there were already many published studies on the chemical composition of galaxies (Tosi 2009, and references therein), Peimbert & Spinrad (1970) were puzzled by the nature of M82 "nuclear" regions with its very bright patches mixed with dark regions on the plane of the almost edge-on (77°) galaxy. Through narrow-band photoelectric photometry of the nucleus and with a bright region of the center they were able to measure the intensity of several emission lines as well as the continuum at different wavelengths and derived an interstellar absorption of 4.23 mag at Hβ for the nucleus. Their study involved the bright region (later denoted as M82 I in paper R-CP) but with the very low resolution of the images obtained with the telescopes and instruments available at that time, it was seen as a single elongated ionized blob and was adopted as the center of the M82 galaxy Peimbert & Spinrad (1970). Once the existence of a second region was established, in R-CP the aim was to investigate which of the two very luminous regions was the center of M82. They were also concerned with the mechanism of the observed ionization and once the intensities of the hydrogen emission lines were obtained together with the observed Balmer decrement they concluded that radiation from supergiant stars (probably dust enshrouded) was the main source of the ionization.

The R-CP study was further motivated by the analysis of a second very bright H II region on several of the first near-infrared images of the center of M82 Raff (1969). Our own detection on a direct hypersensitized infrared plate taken on emulsion I-N (7000–9000 Å) of the two bright H II regions (Figure 3 in R-CP) which was compared with data from the Hα Schmidtobjective prism plate secured by Haro & Rivera Terrazas (1951) showing quite distinctly the H II regions previously reported during the Congreso Científico Mexicano to celebrate the Fourth Centennial of the National Autonomous University

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of México (Figure 1 in R-CP). Making use of the absolute flux derived in Peimbert & Spinrad (1970) for M82 I the intrinsic flux in Hα of region M82 II was estimated. The relative intensities between both regions was found to be 1.2. The physical parameters: diameters of the regions, electron densities, masses of the individual H II regions, Hα luminosities and finally, the number of O6 stars needed to maintain the ionization were presented. The distance to M81 (3.15 Mpc) was adopted to be the distance to M82 as their systemic velocities are similar and as recognized members of the M81 and NGC 3077 group of galaxies (Mayya et al. 2006). It was later confirmed that M82 shares a common large-scale, lumpy envelope of neutral hydrogen gas that extends from M81 encompassing M82 (Gottesman & Weliachew 1977). A revised distance to M82 of 3.63 Mpc is given by Freedman et al. (1994) but the results in R-CP only vary by a few percent. The morphological classifications given by several authors to M82 were as Irr I, I0 and Amorphous by Sandage & Miller (1964).

The radial velocities derived from emission and absorption lines at different position angles and discused in the R-CP paper were aimed to explain the anomalous velocity of M82 II with respect to the rotation curve, nearly 70 km sec^{-1}. The possible ejection of the gas in M82 II from the center of the galaxy was considered as a consequence of the "explosive" event that generated the perturbed aspect of the main body of M82 due the discovery of high-velocity Hα filaments that were thought to be ejected from the nucleus (Lynds & Sandage 1963). Furthermore, it was argued that the ionization present in the two H II regions was not due to the dissipation of the translational kinetic energy associated to the explosion nor to synchrotron radiation as it was previously suggested. The very presence of large numbers of stars currently being formed in the M82 regions I and II studied, were recognized for the first time by R-CP to be the main source of ionization in M82. Even the estimates of the physical parameters were pointing towards what now are the current ideas on the violent star forming regions from 30 Doradus to the Lyman-break galaxies.

More than 1400 papers have been published since R-CP discused the nature of the nuclear region in M82. Most have delt with the nuclear starburst or phenomena related to the starburst activity. We are going to present what we now know about the nature of our "H II regions" in M82 and the well-known place that M82 occupies as the nearest and most studied "starburst" (SB) galaxy in our local Universe. We aim to concentrate on the "super star clusters" (SSC) identified in the nuclear region of M82 and in other galaxies that are presently forming stars in violent bursts episodes. It is worth mentioning that Carrasco et al. (1986) using observations carried out of the nuclear region of M82 with an S-1 image tube attached to the 3 m telescope at Lick Observatory at four different wavelength bands ([SIII] $\lambda\lambda$9069–9530 Å, He λ10830 Å, [SIII] + IR continuum and blue continuum $\lambda\lambda$4000–5000 Å) showed bright knots (Mv = 15) many not previously detected or resolved, concluding correctly that these objects might be ionized regions or superclusters and others as byproducts of the irregular structure of the extinction due to the presence of dust clouds. Therefore the compact objects now known as SSC were called *Superclusters* almost a decade before they were discovered by the Hubble Space Telescope (HST) and eventually called by the same name.

We would like to point out that one of the greater contributions the early paper by R-CP made towards understanding the nature of star-forming galaxies like M82, was to wisely recognize the need to study the nuclear region of M82 at all wave-bands. Particularly, they stressed the need of NIR and MIR studies to overcome the high obscuration in the central regions of galaxies due to dust and gas. Radio and polarimetry observations from other authors were at the time used to identify which of the two H II regions discused was the nucleus. Their insight towards the multifrequency approach is nowadays a standard practice in studying the complex mix of starburst galaxies stellar populations, their high-luminosities, strong non-thermal radio emission, correspondence of radio and IR sources, large populations of red giants and super giants, large UV fluxes and X-ray luminosities.

2. WHAT DO WE KNOW NOW ABOUT M82

In this short commentary, we would like to present new and not very new results on the nature of M82 as a galaxy and how it is forming stars. Some very recent discoveries will be discussed about the existence of structure that was not previously known such as two symmetrical spiral arms detected using observations obtained with our NIR camera (*CANICA*) and spectroscopic observations of the absorption-line dominated stellar spectra at a variety of radial distances from the center of M82 at the Observatorio Astronómico Guillermo Haro (OAGH) in Cananea (Mayya et al. 2006). Together with these observations, the wealth of excelent imaging data from SDSS and HST/ACS in the various filters and the scientific images released by the Heritage Team for the 16 anniversary of the HST, have motivated more investigations towards the nature of the star formation history in the disk and nucleus of M82. Using data from GALEX in the near and far UV, of the nuclear regions of M82 and the disk, the epoch of formation of large numbers of SSC as the source of the large UV radiation that ionizes the central regions of M82 will help to explain the nature of M82 (Mayya et al. 2006, 2008; Rodríguez-Merino et al. 2009). Certainly, 39 years earlier we were trying to explain it with what was then known: violent star formation in our very neighborhood! In M82 we are actually witnessing a galaxy being formed, where gas is being recycled into its central regions and forming stars very efficiently: a phenomenon now known to occur in very far away galaxies at mind-blowing far-IR, mm and sub-mm luminosities.

3. THE CENTRAL REGIONS OF M82

In their classical papers, O'Connell & Mangano (1978, thereafter OM) and Rieke et al. (1980) were the first to dismiss the exotic views on M82 as a galaxy undergoing an explosive event, being the latter succesful explaining all the observed features under the scenario of a starburst model. OM reexamined the complex central region using large scale blue plates taken with the Palomar Observatory 5 m telescope. At the adopted distance to M82 of 3.63 Mpc (Freedman et al. 1994) the scale is one arcsec = 17.6 parsec. Using a blue image (kindly made available to them by A. Sandage) OM identified the largest high surface brightness regions in B (blue) light lying about 1 kpc) of the strong central dust lane. Denoting the largest visible features as A, B, C, (see Figure 3 in OM) they were able to associate the two bright H II regions described by R-CP assigning A to M82I and C to M82II, being A the brightest of the two as previously estimated by R-CP. O'Connell (1970; as in OM) had described the absorption and emission-line spectra as well as Peimbert & Spinrad (1970) and was able to construct a stellar population model for the central regions of M82 to reproduce his high resolution 5 m multichannel scanner observations that indicated that star formation had occurred within the last few million years.

As one can appreciate looking at the bright knots in OM blue images, some features that looked like young star clusters were seen. Although from the optical data alone region A was thought to be the center of the nuclear region, radio and IR data then available indicated a high-luminosity hidden source displaced a few second of arc from region A (or M82I) what is quite probably the nucleus of M82. Their further analysis of Lick plates in Hα interference filters shows nothing else but the concentration of Hα emission to the continuum knots visible there, very much like our own I-N plate (Figure 2 in OM). Other features identified in the blue plates do not show at all in the NIR but the A and C complexes. Almost two decades later, O'Connell et al. (1995) now provided with the first high-resolution V- and I-band images obtained with the *Hubble Space Telescope* Planetary Camera of the center of M82, did identify a complex of over 100 compact, luminous "super star clusters" (Mayya et al. 2008, SSCs). In those high resolution images (scale 0.77 pc per px) one could clearly see several of the high surface brightness knots and complexes identified before in OM (see Figure 1 in O'Connell et al. 1995). In their Figure 3, they present the HST-PC V-band image of the very center of M82 showing the location of the prominent non-optical features most likely defining the (hidden) nucleus of the galaxy.

In what follows we would like to briefly discuss a very succesful study by Satyapal et al. (1995). These authors, using high spatial resolution and moderate Paβ and Brγ Fabry-Pérot imaging observations of the central kiloparsec of M82 as well as near IR broadband imaging observations were able to examine the extinction towards the starburst region, the state of the ionized gas, and the nature of the stellar population. Their values for the derived extinction towards the central starburst region, assuming a dense, mainly foreground, torus surrounding the central stellar clusters was found to vary between values significantly smaller than those adopted in previous studies. Moreover a considerable reduction on their estimate for the intrinsic K-band luminosity of the central stellar component, affects the inferred IMF for the starburst region, being more like that of the solar neighbourhood than previously assumed.

The early suggestion by Recillas-Cruz & Peimbert (1970) concerning the sources of emission in the near-infrared bandpasses and the emission by dust being dominated by starlight is confirmed by this study. Additionally, a detailed comparison of the dust emission feature at 3.29 μm with the Brγ emission and its variation throughout most of the central starburst region along with other star formation diagnostics suggests that the near-infrared continuum emission across the starburst regions is dominated by red supergiants with average effective temperatures ranging from 3600 to 4500 K and roughly solar metallicity (in agreement with the great numbers of red supergiants as Rieke et al. (1980) determined and were the main source at 2.2 μm luminosities detected by them) followed by an outward propagating starburst phenomenon. In a second paper Satyapal et al. (1997) report results of a starburst model constructed in order to further investigate the nature of the *stellar clusters* in the starburst complex.

Comparing new observations with NIR spectroscopy and high spatial resolution imaging in the central 500 pc with their model, they were able to derive that the typical age for the starburst clusters is 10^7 yr. Furthermore, an age dispersion within the starburst complex that is correlated with projected distance from the center of the galaxy is estimated to be 6×10^6 yr. Assuming that the starburst is propagating away from the center, they also estimated its velocity of propagation from the center to be ~ 50 km s^{-1}. So unlike previous studies of models of M82, they succesfully modelled the properties of the individual *stellar clusters* in the central 500 pc region.

Using data obtained in a more recent study by Forster Schreiber et al. (2001), with near-infrared imaging spectroscopy at the 3D instrument and mid-infrared spectroscopy with the *ISO-SWS* of the inner starbursts regions of M82, the physical conditions of the ISM, and the composition of the stellar component populations on spatial scales of a few tens of parsecs to 500 pc were determined. Structures as small as ≈ 25 pc were detected in the complex central regions of the galaxy with the H II regions and cooler stars having very different spatial distributions. Large numbers of closely packed stellar clusters ionizing small clouds were observed and the dominant OB star population as well as the constancy of the structural properties found suggest a similar star-forming regions efficiency and evolutionary stage for the most central 500 pc. Furthermore, these authors suggest that besides tracing the star formation history the OB stars and the red supergiants within the starburst core, up to about 50 Myr, also show evidence of a time sequence in the triggering of the bursts at *different* locations. Therefore they conclude that radial evolution has taken place, as Satyapal et al. (1995) have suggested. In a later paper they conclude that their results are well matched by a scenario in which the global starburst activity in M82 occurred in two successive episodes each lasting a few million years, peaking about 10^7 yr and 5×10^6 yr ago.

They conclude that the first episode took place throughout the central regions of M82 and was particularly intense at the nucleus, while the second episode occurred predominantly in a circumnuclear ring and along the stellar bar. Such a bar was previously detected at 2.2 μm by Telesco et al. (1991) and besides providing the link between the interaction of M82 and M81 is suggested to be the mechanism responsible for triggering the most recent star forming burst near the center of M82. Furthermore, Forster Schreiber et al. (2001) based on radial velocity data from their paper indicate that most sources reside in a nearly edge-on rotating ring at a radius coinciding in projection, as well as along the stellar bar at larger radii, where the most recent starburst episode took place and again proceeded very likely, from the inside out.

The use of high spatial resolution HST optical images and STIS spectra has enabled Westmoquette et al. (2007) to further probe the inner regions previously studied by O'Connell et al. (1995) with two slits crossing four of the optically brightest starburst clumps near the nucleus of M82. These provide Hα kinematics, extinction, electron density, and emission measures. From the radial velocity curves derived from both slits the authors confirm the presence of a stellar bar and further suggest that the formation of a bar, and the existence of a bar is a very efficient method to funnel gas into the nuclear regions in order to build up the required central gas concentration needed to fuel the star forming process as well as fast cluster winds and the production and evolution of the galactic wind. They also derive a new model for the orientation of the bar and disk with respect to the main starburst clumps and the cluster M82-A1.They argue that clump A has formed within the bar region as a result of gas interactions between the bar orbits, whereas region C lies at the edge of the bar and regions D and E are located farther out from the nucleus but heavily obscured, as previously determined.

Using observational data from the HST's 16th anniversary celebrated with the release of the color composite image of M82, Mayya and collaborators (Mayya et al. 2006, 2008; Mayya & Carrasco 2009) started a project aimed at studying the star formation history and the ages of the bursts of star formation in the nuclear regions and in the disk, as well as the future and evolution of the superstar clusters in the frame of M82 as a galaxy. The data they secured was obtained through the Hubble Heritage Team using the ACS WFC in 2006 and released in fits format. Observations consist of many individual exposures in the B, V and I filters covering a field of view of 8×8 arcsec centered in the galaxy nucleus and cover the entire optical disk of the galaxy. The idea was to carry out an objective search of star clusters and identify as many SSCs as possible over this incredible high resolution image of M82. Some

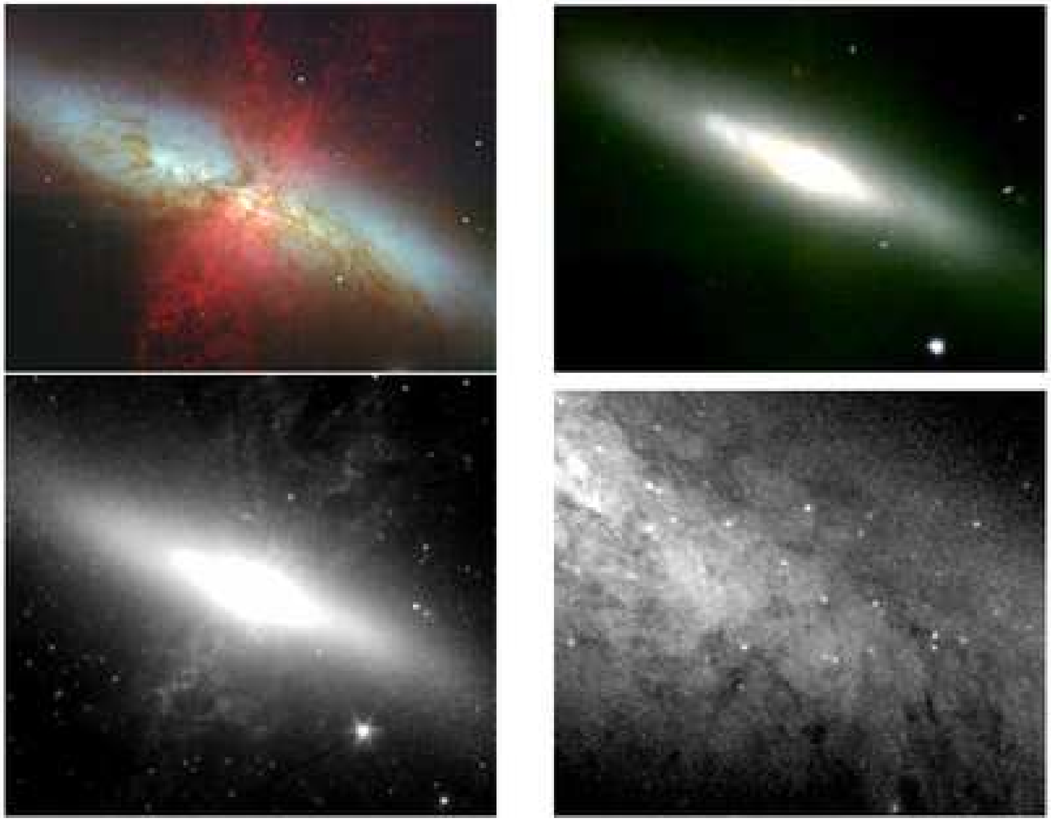

Fig. 1. Multi-band views of M82 illustrating the interplay between stars, gas and dust. In the color composite optical (BV and Hα) Subaru image (top-left), we see the stellar disk and the dust lanes, with the Hα emission tracing a bi-conical structure along the minor axis. In the NIR (JHK; top-right), and Spitzer 3.6 μm (bottom-left) images, the most prominent structure is the central bar, which is completely obscured in the optical image. Filaments along the minor axis of the galaxy in the Spitzer image, trace the distribution of PAH particles and hot dust. A zoom of the SW part of the HST I-band image is shown in the bottom-right panel. Notice the grainy appearance of the image, which is due to the fact that individual stars and compact star clusters are resolved in this image.

of the material available to them is shown in their Figure 1 (Mayya & Carrasco 2009) and reproduced in our Figure 1. In these multiband views of M82, we can see the interplay of stars, gas and dust. In the Subaru image (B, V and Hα) the stellar disk and the dust lanes are seen, with the Hα emission tracing the well known biconical structure along the minor axis. In the NIR (taken with our NIR camera *CANICA* at the OAGH in Cananea) a JHK composite image shows that the most prominent feature is the bar and as can be clearly seen as it dominates over a smooth disk component at these wavelengths. The *SPITZER* image at 3.6 μm, also shows the central bar which is completely obscured in the optical image (Subaru's BV and Hα image). Filaments along the minor axis of the galaxy in the *SPITZER* image, trace the distribution of PAH particles and hot dust, signatures of star forming activity. A close up of the I-band HTS image of the SW region on the external disk of M82, shows a grainy appearance of what are, in fact, individual stars and compact star clusters being resolved in this image.

In the presentation of their studies and results, the nuclear starburst was adopted to be around 500 pc in size and harboring around 6×10^8 $M_\odot$ of mass in stars. Starburst activity in the nucleus is going on in the form of intermittent bursts for the last 30 Myr with two prominent bursts occurring in the last 10 Myr. The search for the SSCs was not confined to the currently active nuclear starburst region, but also in the post-starburst disk of M82. Most of the stars formed in the bursts are concentrated in about 260 clusters in the nuclear region and 393 in the disk (Mayya et al. 2008).

Magnitudes were determined for all the clusters and with the FWHM of these clusters the luminosity and size distribution functions were constructed. The luminosity function follows a power law with an index 2 in accordance to earlier studies (Rieke et al. 1980) with an apparent turnover at the faint end due to incompleteness in the detection of faint clusters and not a turnover in the intrinsic luminosity of the population. Using single stellar population (SSP) synthesis models they derived visual extinction values and photometric masses for the clusters adopting a uniform age of 8 Myr for the nuclear clusters and 100 Myr for the disk clusters. They detected a marginal difference for the power-law mass distribution functions with a steeper index value of 1.8 for the younger nuclear region as compared to 1.5 for the older disk regions. Apparently, the extended low-mass clusters are selectively destroyed during their dynamical evolution, and the larger number of compact clusters in the older sample point towards a mass and size dependent cluster disruption process at work in the disk of M82. Mayya et al. (2008, 2009) have reported a smaller mean size for the older clusters as compared to the younger ones for masses less than 10^5 $M_\odot$, which again imply the selective destruction of loose clusters. This process can be explained through the destruction by tidal forces of the clusters as they orbit around the galaxy. Furthermore, the evolutionary status of the young, and old clusters is of great interest, as it has been recognized as similar in their compactness and mass although the environments in which these two types of clusters are found are widely different. The globular clusters, GC, are found in the halo of galaxies whereas the super star clusters (SSC) are found in the violent star forming regions in the nucleus and in disks. SSC like the ones being studied in M82 and the GC represent the youngest and the oldest stellar systems known in the Universe. It may well be that the compact superstar star clusters in M82 are evolving towards being globular clusters.

4. SUMMARY

We have collected a number of new results on M82 following the 1970 paper by Recillas-Cruz & Peimbert published in the Boletín de los Observatorios de Tonantzintla y Tacubaya (BOTT) which was published under the auspices of the then Observatorio Astrofísico de Tonantzintla in Puebla and the Institute of Astronomy, UNAM, mainly by Guillermo Haro. Now some decades after those first results and published papers, it is proper to give a lasting recognition to our Boletín.

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