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M82 AS A GALAXY: MORPHOLOGY AND STELLAR CONTENT OF THE DISK AND HALO

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RESUMEN

Durante décadas el núcleo de starburst en la galaxia M82 ha acaparado la atención investigándose muy poco acerca de la galaxia en general. En los últimos años la situación ha cambiado con la publicación de varios resultados importantes sobre la morfología y el contenido estelar del disco y del halo. En ésta revisión discutimos nuevos resultados concernientes al esquema general de M82 como galaxia. Desde hace cerca de medio siglo se conoce que M82 no es una galaxia que siga los patrones esperados en galaxias normales, lo que condujo a los morfologistas a introducir un tipo morfológico acorde denominado IrrII o amorfo. Ahora se ha establecido que la razón principal detrás de su aparente diversa morfología, es su historia peculiar de formación estelar, la distribución radial de la densidad del gas y la forma de la curva de rotación. El disco formó casi todas sus estrellas durante un modo de brote hace cerca de 500 Maños, con la formación estelar en el disco completamente agotada en 100 Maños. El registro fósil del brote estelar en el disco yace en forma de cientos de cúmulos estelares compactos similares en masa pero un orden de magnitud más jóvenes, que los cúmulos globulares de la Vía Láctea. La formación estelar que subsiste está restringida a una región central de 500 pc que contiene más de 200 cúmulos estelares jóvenes. El disco contiene un brazo espiral sin formación estelar, no visible en el óptico por la combinacion de extinción y una pronunciada inclinación en la dirección de la visual. El halo de M82 es también poco usual en su contenido estelar con evidencia de formación estelar de bajo nivel que ha ocurrido continuamente por un giga año. Examinamos cuidadosamente cada una de las anormalidades observadas para investigar el efecto global de interacciones en la evolución de M82.

ABSTRACT

For decades, the nuclear starburst has taken all the limelight in M82 with very little discussion on M82 as a galaxy. The situation is changing over the last decade, with the publication of some important results on the morphology and stellar content of its disk and halo. In this review, we discuss these recent findings in the framework of M82 as a galaxy. It is known for almost half a century that M82 as a galaxy doesn't follow the trends expected for normal galaxies that had prompted the morphologists to introduce a separate morphological type under the name Irr II or amorphous. It is now being understood that the main reasons behind its apparently distinct morphological appearance are its peculiar star formation history, radial distribution of gas density and the form of the rotation curve. The disk formed almost all of its stars through a burst mode around 500 Myr ago, with the disk star formation completely quenched around 100 Myr ago. The fossil record of the disk-wide burst lies in the form of hundreds of compact star clusters, similar in mass to that of the globular clusters in the Milky Way, but an order of magnitude younger. The present star formation is restricted entirely to the central 500 pc zone, that contains more than 200 young compact star clusters. The disk contains a non-star-forming spiral arm, hidden from the optical view by a combination of extinction and high inclination to the line of sight. The halo of M82 is also unusual in its stellar content, with evidence for star formation, albeit at low levels, occurring continuously for over a gigayear. We carefully examine each of the observed abnormality to investigate the overall effect of interaction on the evolution of M82.

Key Words: galaxies: individual (M82) — galaxies: starburst — galaxies: star clusters — galaxies: stellar content — galaxies: structure

1. INTRODUCTION

Located at only a distance of 3.63 Mpc (image scale 17.6 pc arcsec^{-1}; Freedman et al. 1994), M82 is one of the most observed objects. The nuclear starburst and the associated galactic superwinds along with the filamentary distribution of dust, not only give it a visually appealing morphology, but also make it an interesting object of study in the entire range of electromagnetic spectrum. It is one

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of the brightest infrared objects in the sky. Historically, M82 was given a morphological class of Irr II by Holmberg (1950), I0 by de Vaucouleurs (1959) and "Amorphous" by Sandage & Brucato (1979). It was referred to as an exploding galaxy by Sandage & Miller (1964) due to the discovery of high velocity Hα filaments that were thought to be ejected from the nucleus.

The exotic idea on the nature of M82 were put to rest by the classical works of O'Connell & Mangano (1978) and Rieke et al. (1980), the latter successfully explaining all the important observed features under the framework of a starburst model. Since then, the nuclear region of M82 is considered an archetype for the starburst phenomenon. The discovery of a bridge of intergalactic gas connecting M82 to its neighbor M81 and subsequent N-body simulations suggest that the starburst in M82 is triggered by an encounter between M82 and NGC3077, both members of the M81 group (Gottesman & Weliachew 1977; Yun, Ho, & Lo 1993).

Though there exist innumerable studies on M82, a vast majority of them discuss the nuclear starburst or a phenomenon related to the starburst activity. However, interest in M82 as a galaxy is growing in recent years. There are suggestions that in M82, we may be witnessing the formation of a new galaxy in our neighborhood. The principal aim of this review is to summarize the known properties of M82 and discuss these properties in the framework of M82 as a galaxy.

In § 2, we briefly discuss the properties of the central kiloparsec, which includes the starburst nucleus and the bar. The properties of the inner stellar disk (1–3 kpc) are discussed in §§ 3 and 4. The outer disk and the halo are discussed in § 5. In § 6, we discuss the significance of the presence of a population of compact star clusters in the disk. M82 as a galaxy and its current evolutionary status are discussed in § 7. Concluding remarks are given in § 8.

2. THE CENTRAL KILOPARSEC

2.1. *The nuclear starburst and its large-scale influence*

The nuclear starburst occupies a region of around 500 pc in size, and harbors around 6×10^8 $M_\odot$ of mass in stars (Förster Schreiber et al. 2001). 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. Most of the stars formed in the bursts are concentrated in more than 200 compact clusters, popularly known as Super Star Clusters[2] (O'Connell et al. 1995; Mayya et al. 2008, SSCs). The energy liberated from massive stars in these clusters is released as galactic superwinds, which are traced by the Hα and X-ray emitting gas as cone-shaped structures along the minor axis of the galaxy up to distances as far as 10 kpc above the galactic plane (Lehnert, Heckman, & Weaver 1999). The central starburst region has a patchy appearance in the optical bands with more than 4 mag of visual extinction if the majority of the obscuring dust resides in a foreground screen and 43–52 mag if dust is mixed with the stars (Förster Schreiber et al. 2001). Surrounding the active starburst region, there is a molecular ring of 400 pc radius (Shen & Lo 1995). The patchy optical appearance and the Hα emitting cone are illustrated as a (color) composite image, formed using the B, V and Hα images taken with Subaru telescope, in the top-left panel of Figure 1 (Ohyama et al. 2002).

The nature of the off-planar structures seen in the Hα images were historically argued to be of explosive origin (Sandage & Miller 1964). However, polarization observations by Visvanathan & Sandage (1972), Schmidt et al. (1976) and Scarrott et al. (1991) established that much of the halo Hα emission is in fact the disk light scattered by the dust particles in the halo. Bland & Tully (1988) and more recently Ohyama et al. (2002) established that it constitutes two components: the first component consists of filamentary, narrow-line emission (full width at half maximum (FWHM) < 200 km s^{-1}) organized into a bipolar outflow over the surfaces of two elongated bubbles, and the second component consists of broad-line (at FWHM 300 km s^{-1}) and continuum emission arising from a faint exponential halo that rotates slowly with the disk. The mid infrared spectra of the halo taken by recent observations by the Spitzer telescope have confirmed the presence of dust in the halo as is illustrated in the bottom-left panel of Figure 1 (Engelbracht et al. 2006).

2.2. *The central galactic components: The Bar and the Bulge*

The almost dust-free vision of M82 in the near infrared bands, allowed Telesco et al. (1991) to discover a bar of $\sim$1 kpc length as soon as the imaging technology became available at these wavelengths. The kinematical data are fully consistent with the stars orbiting in radial orbits along this bar (Wills

[2]It is interesting to note that Carrasco et al. (1986) had identified these compact objects on the photographic images and called them Superclusters almost a decade before they were discovered by the Hubble Space Telescope (HST) and eventually called by the same name.

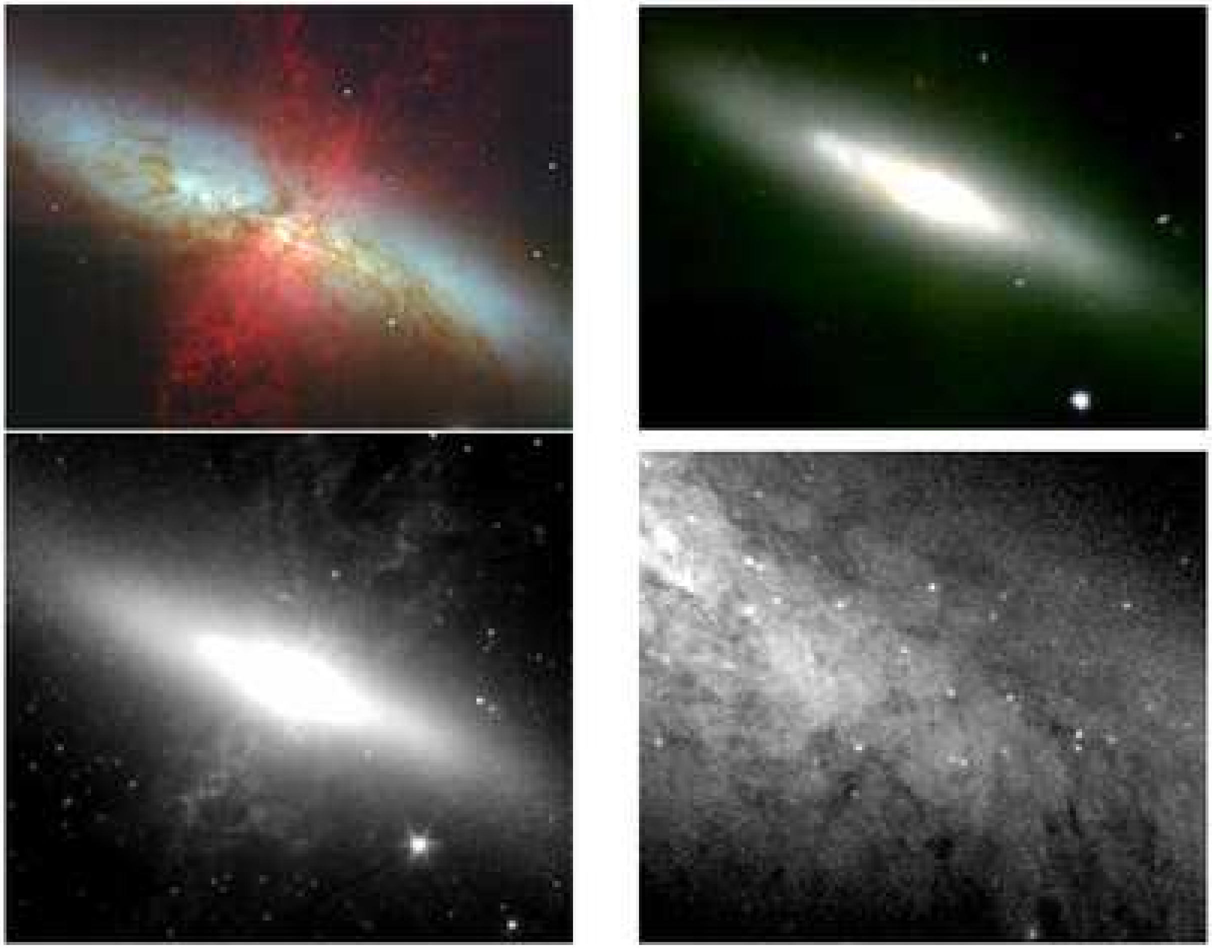

Fig. 1. Multi-band views of M82 illustrating the interplay between stars, gas and dust. In the color composite optical (BV and Hα) Subaru image (top-left), we see the stellar disk and the dust lanes, with the Hα emission tracing a bi-conical structure along the minor axis. In the NIR (JHK; top-right), 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.

et al. 2000). The bar contributes substantially to the dynamical mass in the central region. Sofue (1998) estimated a mass of $\sim 10^{10}\,M_{\odot}$ for the entire galaxy, with most of this mass concentrated within the central 2 kpc. A near infrared (NIR) composite image from Mayya, Carrasco, & Luna (2005) is presented in the right panel of Figure 1, where it can be clearly seen that the bar dominates over a smooth disk component at these wavelengths.

How big is M82's bulge? Sofue (1998) interpreted the entire galaxy as the bulge of what was once a normal late type galaxy. The near infrared intensity profiles (see Figure 2) show an excess nuclear light above that expected for an exponential disk, which was probably interpreted as coming from the bulge component by Sofue (1998). However, a detailed surface photometric analysis of the profiles suggest that the observed excess nuclear light can be completely explained in terms of the contribution from the nucleus and the bar. Gaffney, Lester, & Telesco (1993) have looked for kinematical evidence for the bulge and gave an upper limit of $10^7\,M_{\odot}$ for the bulge mass with a maximum size of 7.5 pc.

3. THE INNER (1–3 KPC) DISK: MORPHOLOGY AND DYNAMICS

3.1. *Optical and near infrared surface photometry*

Detailed optical surface photometric analysis of M82 is hindered by the obscuration caused by the dust along the line of sight, which is expected given

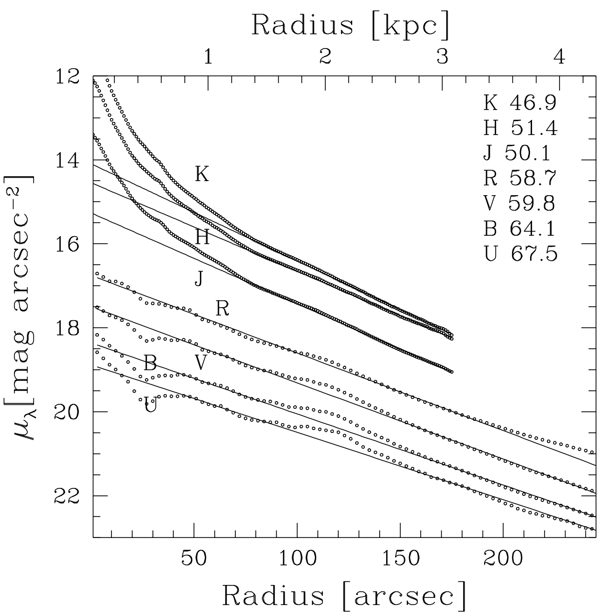

Fig. 2. Multi-band radial surface brightness profiles of M82. The numbers at the top-right corner correspond to the exponential scale length in arcseconds in the indicated bands. Notice the gradual flattening of the profiles at shorter wavelengths. The bar is responsible for the steep increase of intensities in the NIR bands in the central part.

the large inclination of the disk of the galaxy to the sky-plane (77°). Disk outside the central starburst suffers considerably lower extinction — nevertheless the obscuring dust can be easily traced in the optical images even at 2 kpc ($\sim 120''$) distance away from the nucleus. On the other hand, the NIR surface brightness is not affected by the dust. These are illustrated in Figure 1.

Blackman, Axon, & Taylor (1979) made a first attempt to obtain a detailed surface photometry of the disk of M82, using the photographic and electronographic images in the B and V-bands. They found that the profiles for galactocentric distances $R_{\rm G} < 90''$ and $R_{\rm G} > 210''$ are indistinguishable from those of normal, late type spiral galaxies. Between these radii there is evidence for an enhancement which can be attributed to scattering of light from the inner component or disk by dust particles. We confirm their findings using new digital data (Figure 2), where we can clearly see the enhancement as a bump in the radial intensity profiles between $R_{\rm G} \sim 90 - 150''$. The bump is stronger at shorter wavelengths, suggesting that the excess light is relatively bluer — a characteristic property of scattered light. It can also be noticed in this figure, that the profiles at $R_{\rm G} > 60''$ can be very well fitted by an exponential function, with the scale-lengths systematically increasing at shorter wavelengths — again a property characteristic of dusty disks (Evans 1994). The shortest scale-length is reached in the K-band, where the observed scale-length ($47'' = 0.8$ kpc) is expected to represent the scale-length of the mass distribution. In the very central part, there is clearly an excess of NIR light over the exponential disk, which is associated with the central starburst and the bar, first noticed by Telesco et al. (1991).

It may be recalled that the "failure to resolve individual stars or stellar complexes" was one of the defining criteria for the Irr II (or amorphous) morphological class assigned to M82. The amorphous appearance seen on the ground based images of M82, breaks down at the resolution of HST/ACS images (Mutchler et al. 2007), especially in the F814 (I) band as can be seen in the bottom-right panel of Figure 1. At mid infrared wavelengths, Spitzer images show the graininess even at arcsec resolutions (bottom-left panel of Figure 1). The amorphous appearance on the ground-based optical images is caused by the dust scattering which acts to smoothen the images. The contribution of the scattered light progressively decreases at longer wavelengths, paving the way to visualize the inherent morphological structures and individual stars.

3.2. *The spiral arms and the Irr II classification*

The classification of Irr II does not contradict the presence of spiral arms, one of the clearest examples being NGC 972 (Mayya et al. 1998). O'Connell & Mangano (1978) have noted that the gross properties of M82 –its mass, luminosity, size, mean spectral type– are comparable to those of normal late type (Sc/Irr) galaxies. Blackman, Axon, & Taylor (1979), based on the radial intensity profile analysis, suggested that the overall structure of M82 resembled that of late-type spiral galaxies, rather than an irregular galaxy. The presence of spiral arms were always suspected in this amorphous galaxy: N-body simulations of the interaction of this galaxy with the members of M81 group predicted the generation of spiral arms (Yun 1999); feeding of the nuclear starburst suggested the presence of spiral arms, without which it is difficult to explain the transport of gas from several kiloparsec distances to all the way up to the end of the bar (Barnes & Hernquist 1992).

Mayya, Carrasco, & Luna (2005) discovered the spiral arms in M82 by analyzing deep JHK-band images, and using the unsharp masking technique — a method popularized by David Malin for amplification of faint photographic images (Malin 1978). In

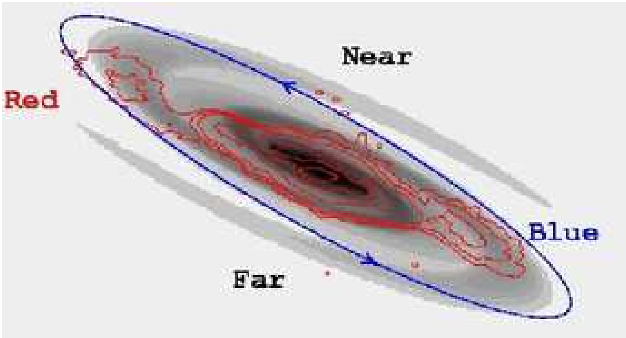

Fig. 3. Illustration of the spiral arms of M82. The gray-scale image shows the spiral arms that best match the K-band residual image (contours), which was obtained by subtracting an exponential disk from the observed image. The ellipse with arrows indicates the sense of rotation of stars expected for trailing spiral arms.

Figure 3, we display the modeled image of the spiral arms. The absence of a dominating bulge, and the relatively open arms (pitch angle=14°) suggest that M82 is a late-type spiral (SBc), which is consistent with the gross properties discussed above.

In normal galaxies, the spiral arms are easily traced in the Hα and the B-band images due to the preferred association of the star forming regions with the arms. We find that the arms of M82 are not forming stars at present. In fact, the entire disk of M82 has stopped forming stars at around 100 Myr ago, as will be discussed in § 4. In the absence of star-forming HII regions, the discovery of arms requires one to trace the underlying stellar continuum emission in the optical and NIR wavelengths. However, (1) the high obscuration caused by dust, (2) decreased contrast of the arms due to the scattered light, and (3) the nearly edge-on orientation of the disk make the detection of the spiral arms in the optical images an impossible task. The first two effects can be partly overcome by using the NIR images. However, NIR band has a dis-advantage for searching spiral arms — spirals are generally bluer than the surroundings making the spirals intrinsically less prominent at the NIR wavelengths. Thus, it is not surprising that the spiral arms could be detected only after subtracting the smooth exponential component even in the NIR images.

3.3. *The gas and dust content*

Late-type spiral galaxies are rich in gas content, with the neutral gas extending all the way up to, and some times even beyond, the optical disk. M82 as a galaxy is abnormally gas-rich with the gas fraction by mass being as high as 30–40% (Young & Scoville 1984). However, most of the disk gas is concentrated in the central 1 kpc region. There exists gas outside this radius but most of it is warped southwards in the direction of its companion M81 (Yun, Ho, & Lo 1993; Walter, Weiss, & Scoville 2002). Thus much of the disk of M82 is gas-poor.

Almost all of the Hα emission lies in the nucleus and the halo, with HII regions not even detectable in the spiral arms. However, there is ample evidence for the presence of dust in the inner disk. These evidences are: (1) spectra all the way to 3 kpc show Na absorption lines, whose strength and line width suggest their interstellar origin (Goetz et al. 1990), (2) spectral energy distribution of the disk obtained from long-slit spectra and multi-band photometry suggests a visual extinction of ∼1 mag (see the contribution of Rodríguez-Merino et al. 2010), and (3) the cluster colors suggest the presence of extinguishing dust at parsec scales (Mayya et al. 2008).

3.4. *The mass and mass-to-light ratio*

The rotation curve of M82 has been derived in several studies using both stellar and gaseous tracers up to a radius of 170″. Mayall (1960) and Goetz et al. (1990) obtained a rotation curve using optical emission and absorption lines, whereas Sofue (1998) used the CO and H I lines. In all these studies, the rotation curve has been modeled to obtain the radial distribution of mass. In the radial zone between 70–170″, Mayall (1960) estimated a mass of $4 \times 10^9 M_\odot$, whereas the masses estimated by Goetz et al. (1990) are $\sim$ 50% lower. Sofue (1998) found that most of the mass is concentrated within the central 1 kpc radius, with the mass distribution outside this radius consistent with an exponential mass surface density profile. Significantly, there is no evidence for a dark matter halo, and hence the entire mass outside the central bar can be associated with the stars and gas in the disk.

We compiled all the reliable velocity data from the literature and re-calculated the maximum mass that the data permit outside the nuclear starburst zone for an exponential mass distribution of scale-length 48″, the value derived from the K-band image. The resulting fits to the observed rotation curve are shown in Figure 4. It can be seen that the peak of the rotation curve is reached at a radius of 30″, with the disk mass outside this radius contributing very little to the observed velocities. The peak velocity measured using the cold gas tracers (HI and CO by Sofue (1998)) is substantially higher than the optical tracers, with the result that the inferred mass in the starburst region is a factor of 2.5 higher for the former. However, both the tracers give a maximum

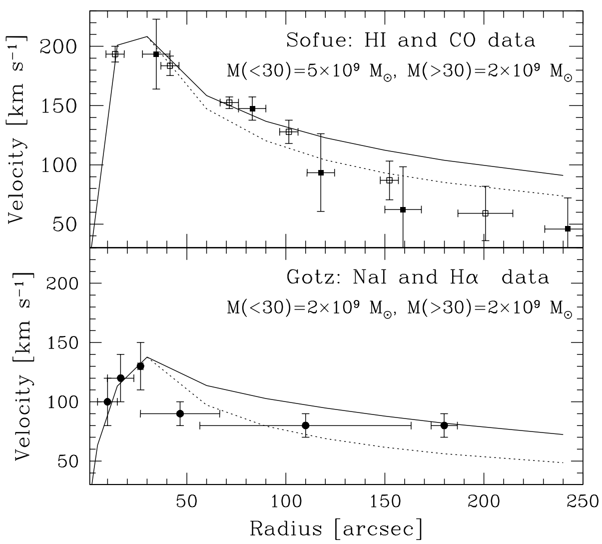

Fig. 4. The rotation curve and mass model for M82 using cold gas (top) and stellar and ISM absorption line (bottom) velocity measurements. The vertical error bars denote the errors in the measured velocities. The horizontal error bars denote the beam size in the top panel and the range of radius where the measured velocities remain almost the same, in the bottom panel. The dotted line corresponds to the rotation curve for a mass distribution that is entirely concentrated within the 30″ radius (solid body inside, and Keplerian outside this radius). The effect of adding an exponential disk of scale length 48″ is shown by the solid line.

mass of $2 \times 10^9\ M_\odot$ outside this zone, which is consistent with the values derived by Goetz et al. (1990). Given that both the HI and CO have been detected in the cone of gas that is outflowing from the nuclear zone, and also along the off-planar streamers, the velocities measured by these tracers may not represent the circular velocities in the plane. Hence, velocities measured by the optical tracers, especially the stellar absorption lines such as the Balmer lines, are expected to be more representative of the circular velocities.

We obtained the M/L_K of the disk outside a radius of 1 kpc by combining the disk mass and the K-band luminosity in the same radial zone (70–170″). The resulting value is $0.15 \pm 0.05\, M_\odot/L_{K\odot}$. At least 15% of the disk mass in the radial zone outside 70″ is in the form of atomic and molecular gas (Young & Scoville 1984). For comparison, $M/L_K = 1$ if the typical stars are solar-like. The observed low value of M/L_K indicates that the disk is dominated by stars that are more massive than the Sun, consistent with the A–F spectral classification assigned for this galaxy by Morgan (1958).

4. THE INNER (1–3 KPC) DISK: STELLAR CONTENT

4.1. *Age of the dominant stellar population*

Mayya et al. (2006) used the long-slit spectra along the major axis of M82 to age date the dominant stellar population on either side of the nucleus. The position of slit along the major axis as well as the identification of some of the age-sensitive absorption features are shown in Figure 5. Each spectra is obtained by averaging the long-slit spectra spatially over a width of 40–50″. Spectrum corresponding to 60″ radius on the northeast side encloses the bright optical patch known as "M82-B". The four spectra corresponding to radius $\leq 110''$ are strikingly similar. The outer spectra show a slight difference in the relative intensities of the Ca II K & H lines, with respect to the inner disk spectra.

Comparison of the features in the observed spectra to those from a Single Stellar Population (SSP) model, gives an age of 0.5 Gyr for the populations for the disk interior to 110″ radius (i.e. < 2 kpc). More importantly, the spectra are not consistent with mean ages greater than 0.7 Gyr. The 160″ spectra (2–2.7 kpc radial zone) suggest a population that is marginally more evolved as compared to that of the inner part of the disk, with an age of 0.9 ± 0.1 Gyr.

4.2. *Global Star formation history*

From the discussions above, it is clear that the inner disk of M82 has a low M/L_K, and a young mean age, as compared to those for a normal disk of a late-type galaxy. Detailed analysis of abundances of elements in cold, warm and neutral gas, suggests that the α elements are systematically enriched (Origlia et al. 2004). These are unmistakable signatures of a disk seen immediately after a major star-burst. Detailed modeling of these data suggest that almost all the observed stellar mass of the disk was part of a burst lasting for only a few hundred million years, the burst having completely stopped around 0.5 Gyr. The resulting star formation history is shown in Figure 6. Further details of the model can be found in Mayya et al. (2006).

4.3. *Spatially resolved star formation history from star counting*

A recent study by Davidge (2008a) using the IR color-magnitude diagrams for the resolved red stars threw more light not only on the evolutionary status of the inner and outer disk, but also that of the halo. In this section, we discuss the results pertinent to the inner disk, postponing the discussions of the

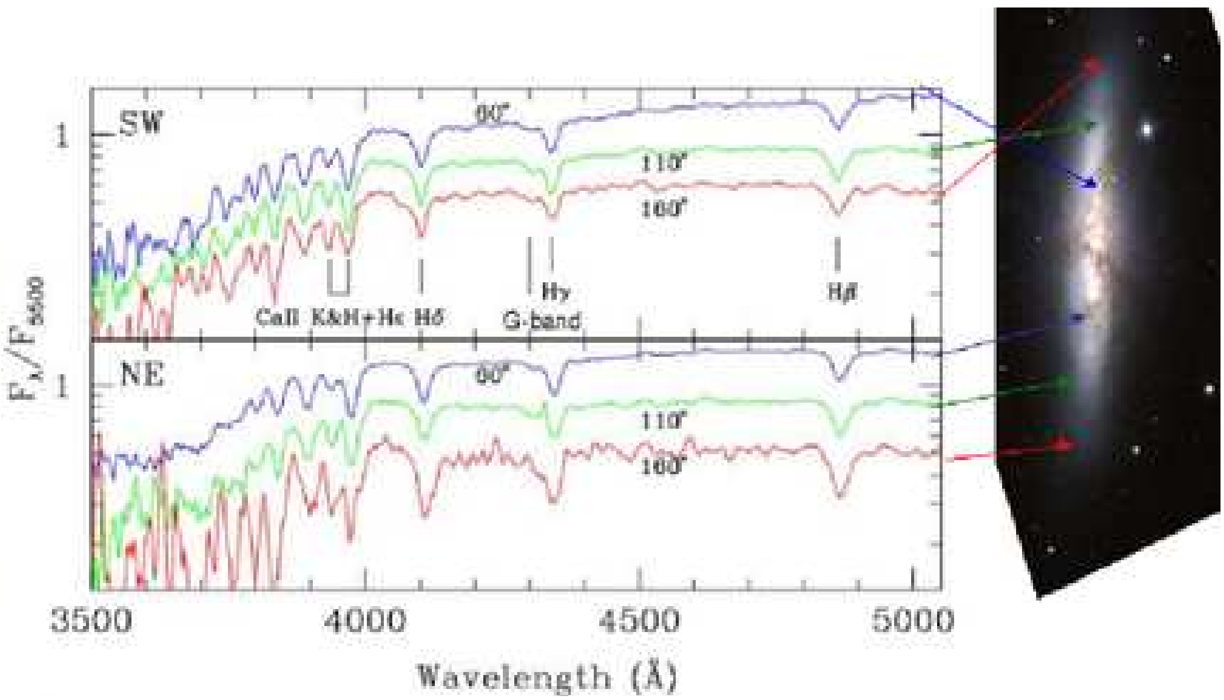

Fig. 5. Blue part of the major axis spectra extracted on either side of the center at three radial zones centered at galactocentric distances of 60″, 110″, and 160″ are shown. Approximate positions of the extracted spectra on an optical image are shown by the arrows. Prominent age-sensitive features are indicated.

results for the outer disk and halo to the next section. Deep wide-field images taken with the *MegaCam* and *WIRCam* instruments on the Canada-France-Hawaii Telescope (CFHT) were used in his work to trace the brightest stars seen longward of the traditional R-band. Specifically, r', i', z', J, H and K-bands were used. The exposures were long enough to allow the detection of the asymptotic giant branch stars (AGBs) in M82.

One of the aims of Davidge's study was to test the burst nature of star formation in the inner disk predicted by us (Mayya et al. 2006). According to the burst model, the disk should mostly contain stars that are older than 0.5 Gyr. According to the isochrones of Girardi et al. (2002), stars are in their AGB phase at these ages, which are above the detection limits of the CFHT observations. Additionally, the disk is not expected to contain stars that are formed relatively recently, such as OB stars, and Red Super Giants (RSGs). From the analysis of color-magnitude diagrams (CMDs), Davidge firmly established the absence of these relatively younger stars in the entire disk. He found that the brightest stars populating the CMDs are the AGB stars. The progenitors of these stars are of a few solar masses, with the brighter AGBs being slightly more massive and younger as compared to the relatively fainter AGBs.

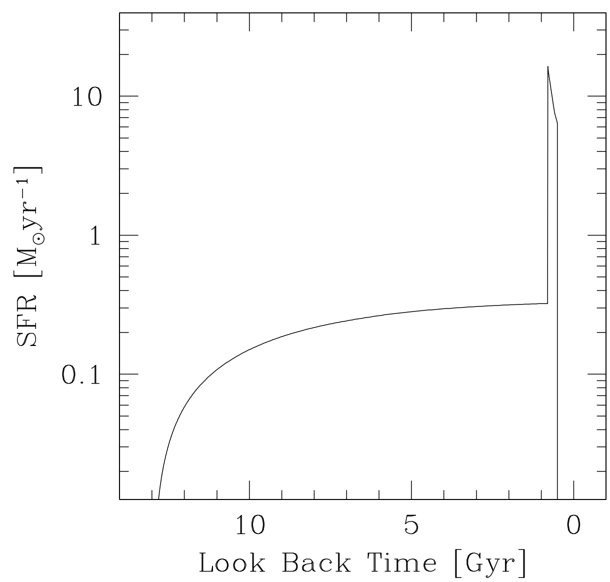

Fig. 6. Star formation history of the disk of M82 that reproduces best the observed properties. More than 90% of the observed disk mass is produced in the burst.

The i'-band luminosity function for the inner disk (2–4 kpc) is reproduced in the top panel of Figure 7.

It has a peak at $i' = 23.4$ mag, the number density of stars dropping significantly on either side of the peak. The brightness corresponding to the peak is more than a magnitude brighter than the limiting magnitude, suggesting that the peak is real and not due to the incompleteness on the fainter side. Given the one-to-one relation between the age and magnitude during the AGB-phase, the luminosity function can be used to infer the star formation histories (SFHs). The observed luminosity function resembles exactly that expected for a burst mode of SFH. The peak corresponds to a peak in the starburst activity at ~ 0.5 Gyr ago. There are hardly any stars brighter than $i' \sim 22$ mag, implying the absence of stars younger than ~ 100 Myr.

Another finding in our study is that only less than 10% of the presently observed disk mass is contributed by the stars older than about 1 Gyr. Otherwise, the disk stellar mass would exceed the observed dynamical mass for the inner disk. Data give an indication of a decrease in the number density of stars older than ~ 1 Gyr. However, the detection limit and the present status of understanding of the evolution of AGB stars, do not allow a conclusive answer about the absence of these older stars.

Thus, star formation history derived from the resolved stellar population is in excellent agreement with the burst model we had proposed. These new observations can be used to fine tune the burst model. It seems the burst strength decreased gradually after it peaked at ~ 0.5 Gyr, continuing up to 100 Myr ago, terminating abruptly at this age. The continuation of the burst to relatively younger ages as compared to our model, implies that the M/L_K could be accommodated with slightly more mass in the pre-burst stars. Thus the mass in these stars could be slightly higher than the 10% of the disk mass predicted by us.

5. THE OUTER DISK AND THE HALO

5.1. *The outer stellar disk*

The short scale length of the M82 disk implies that the disk intensity falls more rapidly with radius in this galaxy as compared to that in normal late-type galaxies. As a consequence most of the detailed information on the disk exists only for the inner 4 kpc. The disk size defined as the radius at which B-band surface brightness falls to 25 mag arcsec^{-2} is as big as $6.5'$ (6.9 kpc). Thus the discussions of the previous sections pertained to basically the inner half of the disk. From now-on-wards, we refer to the part of the disk at galactocentric distances greater than 4 kpc as the outer disk.

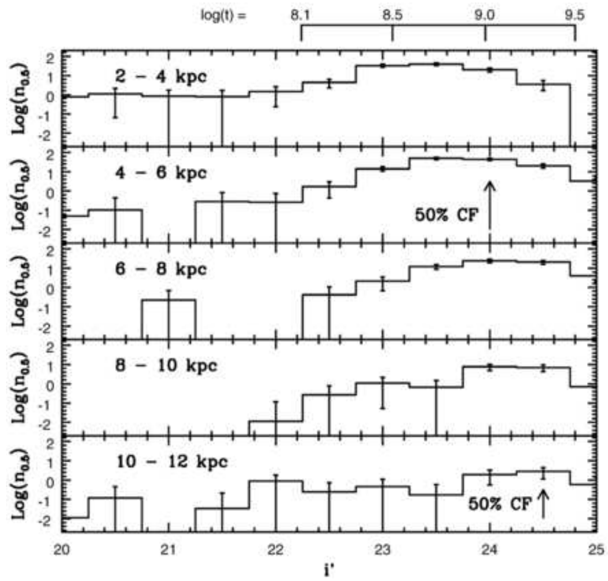

Fig. 7. The i'-band Luminosity Functions (LFs) of stars in the M82 disk. $n_{0.5}$ is the number of stars with $r' - i'$ between 0 and 2 per 0.5 i' mag per arcmin^2. See Davidge (2008a) for more details.

Did the outer disk also participate in the large-scale starburst following the interaction? Does it also lack stars older than the burst? Obtaining spectra that could be used to age date the outer disk ($\mu_B > 22$ mag arcsec^{-2}) is challenging even for the largest present-day telescopes. In the absence of spectroscopic ages, approximate ages of the prominent stellar population could be estimated using the mass-to-light ratios. However, the outer disk lacks a commonly used tracer of rotation curve such as Hα, or HI, and hence the dynamical mass estimates are not available.

The CMD of resolved stars in the NIR bands offers an alternative way to determine the ages of stellar populations and SFH of the outer disk. Using such a technique, Davidge (2008a) found that the AGB stars are the brightest NIR stars in the outer disk, similar to the results found for the inner disk. AGB stars are detected even at radial distances as far out as 12 kpc from the center. Throughout the outer disk, there is a clear lack of stars younger than ~ 100 Myr, which suggest complete cessation of star formation activity in the last 100 Myr. The i'-band LF for three radial zones are displayed in the bottom three panels of Figure 7. It can be seen the SFH of the outer disk is qualitatively very similar to that of the inner disk. In the figure, we can see a trend of the peak of the LF shifting systematically to fainter magnitudes at larger radius. The existence of a peak before the 50% confusion limit suggests that the star formation in these parts of the disk also occurred in a burst mode, and that the observed trend suggests that the most active period of star formation was systematically earlier farther out in the disk. At around 10 kpc distance from the center, the burst seems to have started around 3 Gyr ago.

The above ages should be considered tentative, until they are corroborated with observations that go around 1 or 2 magnitudes deeper. If they are found to be correct, then it calls for a new modeling regarding the triggering of the burst. M82 went through an interaction with the members of M81 group around 500 Myr ago. The age of the burst in the inner disk is consistent with the idea that the interaction was responsible for its triggering. However, if the bulk of the red population is as old as 3 Gyr, then clearly the burst couldn't have been triggered by the latest interaction.

5.2. *The stellar halo*

Sakai & Madore (1999) used the HST/WFPC2 V and I-band images to study the properties of the resolved stellar populations of two adjacent fields in the northeast part of the halo. The limiting magnitude in these fields was around 1 magnitude below that expected for the tip of the red giant branch (TRGB) stars, and the crowding of stars was not a serious problem in defining the TRGB. In both the fields, they detected large quantities of RGB stars, and also candidates for AGB stars. One of their fields passed through the off-planar HI filament, where they found significantly higher fraction of AGB stars, indicating the presence of intermediate age populations. Davidge et al. (2004) studied a region in the halo at a projected distance of ~ 1 kpc south of the M82 disk plane, using the H and K'-band images at $0.08''$ FWHM and found conclusive evidence for the presence AGB stars.

In a more recent work, Davidge (2008a) studied the population residing in the halo along the minor axis of the galaxy. AGB stars were detected even at 7 kpc distances about the disk plane. But unlike in the disk, stars of younger ages are also found in the halo. Davidge argued that the majority of halo stars are formed in situ in small associations or clusters and then dispersed to form the diffusely distributed population in the halo. It may be noted that there are several isolated Orion-like star-forming regions in the intra-group medium of M81 group (de Mello et al. 2008), including one ~ 6 kpc to the south of M82 (Davidge 2008b).

Saito et al. (2005) had reported the discovery of two globular clusters at the extreme south of the galaxy. Davidge (2008a) also encountered 5 objects that can be candidates for globular clusters. However, all these objects lie in the direction of M81, putting some doubts regarding their affiliation to M82.

6. THE SUPER STAR CLUSTER POPULATION IN THE POST-STARBURST DISK

One of the biggest achievements of the HST is the discovery of the blue compact star clusters in external galaxies, frequently referred as Super Star Clusters or SSCs. Starburst activity seems to be the necessity condition for their formation and the starburst nucleus of M82 is one of the first regions where SSCs in large numbers are found (O'Connell et al. 1995). If the disk of M82 suffered a large-scale starburst following its interaction with the members of M81 group, then it is very likely that several SSCs were formed, and are still surviving. The wide field imaging capability of the ACS provided an opportunity to search for the SSCs in the disk of M82. A rich population of clusters is indeed discovered, some of which can be easily noticed in the bottom-right Figure 1 (bright points). The details of the search and their properties including their evolutionary status are published in Mayya et al. (2008). Here, we discuss the properties of the cluster population from the point of view of M82 as a galaxy.

A total of 653 clusters were found, nearly 400 of these situated outside the nuclear zone. Spectroscopic ages are available only for a handful of these clusters, with none of the clusters older than 200 Myr (Konstantopoulos et al. 2008). Given that the disk is not heavily affected by the obscuration by dust, optical colors can be used for estimating the ages of the clusters. Both the $V - I$ and $B - V$ colors are consistent with an age of less than 0.5 Gyr, with the visual extinction of around 1 mag. The radial distribution of the number and derived mass of the clusters is given in Figure 8. The cluster density is maximum within 200 pc of the nucleus, thereafter decreasing almost monotonically. The mean as well as the maximum mass of clusters are the highest at around 0.5 kpc distance from the nucleus, just where the bar ends. The mean cluster mass decreases as a function of its distance from the center.

There are no detectable clusters at galactocentric distances greater than 4 kpc. The ACS images cover around 6 kpc distance along the major axis on either side of the nucleus. In addition, given the low surface brightness of the outer disk, the detection limit is more than a magnitude fainter than in the inner disk. Hence, the non-detection of compact clusters in the outer disk is intriguing.

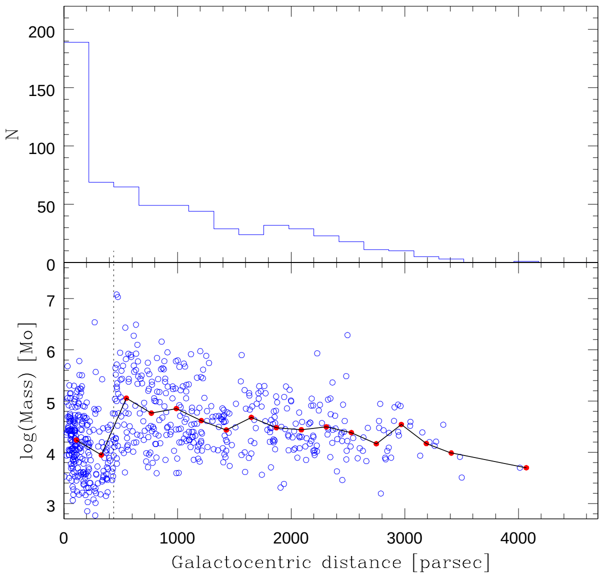

Fig. 8. Radial distribution of the number (top) and mass (bottom) of the Super Star cluster population in M82. The mean mass of the cluster population at each radius is shown by the solid line. The dotted vertical line in the bottom panel divides the nuclear clusters from the disk ones.

The absence of SSCs in the outer disk could be either because the conditions were not suitable for the formation of SSCs or that the SSCs there are preferentially destroyed. On an average SSCs are less massive and more extended at larger galactocentric distances, making them more and more vulnerable to the destruction by tidal forces. Thus, even if SSCs were formed in the outer disk, they could have been destroyed.

7. M82 AS A GALAXY

The low inferred mass, absence of a dominating bulge and relatively open nature of the newly discovered spiral arms all point to a late morphological type for M82. The relative scarcity of globular clusters is also consistent with a late morphological type. Davidge (2008a) compared the stellar properties of the disk of M82 with NGC 2403, a late type isolated galaxy with mass similar to that of M82. He found that M82's stellar disk extends at least up to 12 kpc, which is comparable to the size of the stellar disk of NGC 2403 ($\sim$ 14 kpc), inferred using the same technique as in M82. He also found that the number of bright AGB stars per unit surface brightness (in the K-band) in the outer disks of M82 and NGC 2403 are similar.

However, M82 differs from normal spiral galaxies in the following ways: disks of normal spiral galaxies are characterized by star formation that is continuing uninterrupted over the Hubble time, with mean stellar ages of > 5 Gyr (Kennicutt et al. 1994). On the contrary, there are no stars formed in the recent 100 Myr in the disk of M82 and most of the disk stars are formed in a burst with mean age as young as 0.5 Gyr. This peculiar SFH makes M82 deviate from the normal galaxies in the relations between global parameters: it is too bright and also metal rich for its relatively low estimated mass of $\sim 10^{10}\ M_{\odot}$ (Karachentsev et al. 2004).

It is interesting to note that a number of interacting galaxies also show disk-wide star formation at present: examples being NGC 4038/9, Arp 299 and NGC 4676 (Mirabel et al. 1998; Hibbard & Yun 1999; Xu et al. 2000). This kind of widespread star formation in galactic disks is probably induced by shocks generated in the interstellar medium following the interaction (Barnes 2004).

If the disk-wide starburst happened in the existing stellar disk, then we should be able to infer the presence of such a disk through observations of the pre-burst stars. As of now there is no compelling support for the existence of such a disk. This gives rise to two possibilities: (1) the pre-collisional disk was intrinsically of low surface brightness (LSB), or (2) it was a normal late-type galaxy, but its disk, along with the metal-enriched gas was stripped during the collision. Alternatively, M82 could be in the process of formation, with the starburst being the first major event of star formation in a purely gas-rich galaxy. We discuss these three cases individually below.

7.1. *Gas accretion and starburst in an LSB galaxy*

Mihos (1999) discussed pre-collisional galaxy properties that favors star formation in the disk, before the burst is turned on in the center. He found that the pre-collisional galaxy should be a normal high-surface brightness galaxy with a big bulge or a gas-rich LSB galaxy. If the pre-collisional M82 had a big bulge, it would have survived the interaction (Sofue 1998). However, the observed bulge of M82 is small, consequently, pre-collisional M82 should have been a gas-rich LSB galaxy. Even if the LSB galaxy was gas-poor to begin with, it might have acquired vast amounts of gas as it drifted through the clouds in the intra-group medium of M81 as suggested by Young & Scoville (1984). Deep observations aimed at detecting a stellar disk with properties expected for known LSBs would be required to test this scenario.

7.2. *Rejuvenated star formation in a stripped stellar disk*

In the scenario proposed by Sofue (1998), a disk of old stars is not expected underneath the newly formed disk. Instead, the old stars from the stripped stellar disk and the halo should be found somewhere in the M81 group. In recent years several fields in the intergalactic medium in the M81 group had been the target of HST observations. However, none of these studies so far have reported the discovery of stripped stars. It should be noted that the majority of the pre-collisional stars are expected to be low-mass main sequence stars, which are below the detection limit of the HST observations. The brightest pre-collisional stars are expected to be RGB stars, which are also not detected in the intra-group medium. Sakai & Madore (1999) detected the RGB stars in the halo at a radial distance of 2 kpc. The stripped stars are expected to be much farther than this, else they would have contributed to the rotation curve.

However, not all the available data today favor this hypothesis. For example, according to this hypothesis stellar content and velocity field of M82 should be dominated by those typical of bulge stars. On the other hand, the stars dominating the light immediately outside the nuclear region are much younger than that in typical bulges, and the velocity fields are dominated by the bar potential rather than the bulge (Wills et al. 2000).

7.3. *A nearby galaxy in formation?*

M82 resembles the luminous blue compact galaxies seen at redshifts 0.2–1.0 in having high luminosity, short scale length, a nuclear starburst and low mass (Noeske et al. 2006). Thus in M82, we may be witnessing stars being formed for the first time in its disk, probably in the debris left behind in the interaction. In other words, M82 could be a nearby galaxy in formation. If this is the case, then the detection of RGB stars in the halo of M82 may have been acquired recently.

While we can not rule out completely none of the three models proposed here, majority of the observations favor the starburst in a gas-rich LSB model.

8. SUMMARY AND FUTURE RESEARCH

Studies in the last decade have undoubtedly established that M82 is a late type spiral galaxy. Its unusual optical appearance, which was responsible for its distinct historical classification, is the combined effect of dust scattering, high inclination, and peculiar star-formation history. The disk of the galaxy formed most of its stars in a burst mode, rather than continuously over the Hubble time like in normal late type galaxies. The disk-wide burst model was initially proposed based on the data on the inner disk (radius $<$ 3 kpc). However, recent data on the outer parts suggest that the burst model is applicable as far out in the disk as 12 kpc radius. The star-formation in the disk was completely quenched following the burst, as evidenced from the lack of stars younger than $\sim$ 100 Myr anywhere in the disk. The data seem to suggest that the starburst activity stopped systematically at earlier times at distances farther out in the disk. It may be possible that the starburst activity first started in the outer disk, which then moved progressively to inner radii.

It is now well established that the burst activity of the inner disk is related to the latest encounter between M82 and its neighbors M81 and NGC 3077. According to the scenario proposed by Sofue (1998), the interaction happened around 1 Gyr ago. Numerical simulations of Yun (1999) indicate that the last encounter happened more recently, around 300 Myr ago. In the burst model that best fits the observational data for the inner disk, the burst started around 800 Myr ago, and lasted for around 300 Myr. The duration, as well as the commencement of the burst were mainly constrained by the observed M/L_K, which may be uncertain by a factor of two. If we take into account this uncertainty, data can be reconciled with younger burst ages. Thus the stellar population ages in the inner disk are in general consistent with the idea that the burst was triggered by the interaction. The same is not true for the outer disk, where the bulk of the population seems to be as old as 1 Gyr. At distances 10 kpc away from the center, majority of the AGB stars seems to be as old as 3 Gyr. So if the star formation started in the outer disk, and subsequently propagated inwards, then the burst should have initiated before the latest encounter. Was the encounter happened much before the present estimates or was the starburst related to any earlier encounter?

The pre-burst stellar disk of M82 most likely resembled that of a low surface brightness galaxy. Detection of such a disk using the traditional surface photometric techniques is difficult due to the presence of the glare of the burst stars. Identification of the pre-burst stellar population in the CMD would be the surest way for testing the existence of the pre-collisional disk. These stars are expected to be occupying the main sequence and red giant branches of the CMD. The detection limit in the study of

Davidge (2008a) was not deep enough to identify these stars. The limiting magnitude for point sources of HST/ACS observations of M82 is above the main sequence turn-off magnitude, but are well below the tip of the RGBs. Hence, these images especially at radius greater than 2 kpc could be used for the detection of RGB stars. As of now, such a study was carried out only for the halo, resulting in the discovery of RGB stars (Sakai & Madore 1999). Detection of RGB stars in the disk will not only put strong constraints on the mass of the stars formed before the starburst, but also would help in understanding the evolutionary state of M82.

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