A Massive Star Odyssey, from Main Sequence to Supernova
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M 82: starburst Rosetta Stone

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Abstract. We present evolutionary synthesis modeling of the nuclear regions of the starburst galaxy M 82, based on near-infrared integral field spectroscopy and mid-infrared *ISO* spectroscopy. Our data indicate the occurrence of two distinct starburst episodes in the central 500 pc about 8 - 15 Myr and 5 Myr ago, each lasting a few million years only. The first burst was most intense within 50 pc of the nucleus while the second burst took place in a circumnuclear ring of radius ~ 85 pc and along the stellar bar at larger radii. These recent episodes succeeded earlier starburst activity ~ 1 kpc away from the nucleus and peaking 650 Myr ago, as traced by the luminous star clusters studied by de Grijs *et al.* (2001). The combined results of both studies reveal complex evolution of starburst activity in M 82 which is consistent with a tidally-induced bar-driven scenario.

1. Introduction

In recent years, it has become evident that starburst galaxies are important constituents of the Universe at all accessible redshifts. However, a detailed and quantitative understanding of the starburst phenomenon is still lacking. Crucial issues still open include the initial mass function (IMF) of the stars formed in starburst environments, the evolution of starburst activity, and its triggering and quenching mechanisms. Progress has been hindered by the scarcity of spatially detailed observations and by large dust obscuration often hampering high angular resolution studies at optical/UV wavelengths. Investigations of local starburst galaxies thus remain extremely relevant.

M 82, as one of the nearest (3.3 Mpc, implying $1'' \approx 16$ pc; Freedman & Madore 1988) and most studied starburst, undoubtedly represents a Rosetta Stone in the quest to understand the starburst phenomenon. Extensive studies of M 82 have been carried out at all accessible wavelengths, providing a wealth of observational data for a detailed and consistent characterization of its starburst activity. The central 500 pc of M 82 harbour the most active regions; this 'starburst core' is severely obscured by large amounts of dust partly due to a high inclination of ~80°. A prominent nucleus, a stellar disk, and a kiloparsec-long stellar bar are revealed in near-infrared continuum light. Circumnuclear concentrations of molecular gas surround the starburst core at a radius of ~400 pc while the H II regions are distributed mainly in a ring of radius 85 pc and along the stellar bar at larger radii. An important series of young compact radio supernova remnants extends fairly uniformly along the galactic plane over 600 pc and a bipolar outflow traces a starburst wind out to several kiloparsecs. Over 200 compact and luminous stellar clusters have been resolved by optical *HST* imaging across the central ~1 kpc. Beginning with the seminal paper by Rieke *et al.* (1980), several authors have used evolutionary synthesis to constrain the star formation parameters and history in M 82. However, most models were applied to the starburst core as a whole (*e.g.*, Rieke *et al.* 1993) or to selected stellar clusters (Satyapal *et al.* 1997), and thus may only provide an incomplete picture. More exhaustive reviews are given by, *e.g.*, Telesco (1988), Rieke *et al.* (1993), and de Grijs, O'Connell & Gallagher (2001).

We summarize here our results of near-infrared integral field spectroscopy and mid-infrared spectroscopy of the most active starburst regions of M 82, focussing on the star formation history as traced by massive stars. The near- and mid-infrared regimes are rich in starburst signatures and probe deep into obscured star-forming regions (*e.g.*, $A_{2\mu m} \simeq 1/10\, A_V$). Our spatially and spectrally detailed data allowed us to model the observed regions 'continuously' in space on scales of ~25 pc and in time up to ~50 Myr ago. We interpret our results together with those of de Grijs *et al.* (2001) on the 'fossil' starburst regions further out in the disk. The combination of both studies provides unique quantitative constraints for the evolution of starburst activity in M 82. A full account of our work is given by Förster Schreiber *et al.* (2001; 2002).

2. Probing M 82's obscured starburst: near- and mid-infrared data

The near-infrared data were obtained with the 3D integral field spectrometer (Weitzel *et al.* 1996) of the Max-Planck-Institut für extraterrestrische Physik (MPE). We mapped in H- and K-band a region of $\sim 16'' \times 10''$ (260×160 pc) including the nucleus and extending to the west along the galactic plane out to the inner edge of the molecular ring. The reduced data have an effective angular resolution of 1.5″ (25 pc) and spectral resolution of $R \equiv \lambda/\Delta\lambda \simeq 1\,000$. We complemented these observations with 2.4 - 45 μm spectroscopy at $R \approx 500$ - 1 000 from the Short Wavelength Spectrometer (SWS, de Graauw *et al.* 1996) on board the Infrared Satellite Observatory[1] (*ISO*, Kessler *et al.* 1996). The SWS $14'' \times 20''$ to $20'' \times 33''$ apertures are approximately centered on and include the area mapped with 3D.

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[1] *ISO* is an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands, and the United Kingdom) and with the participation of ISAS and NASA. The SWS is a joint project of SRON and MPE.

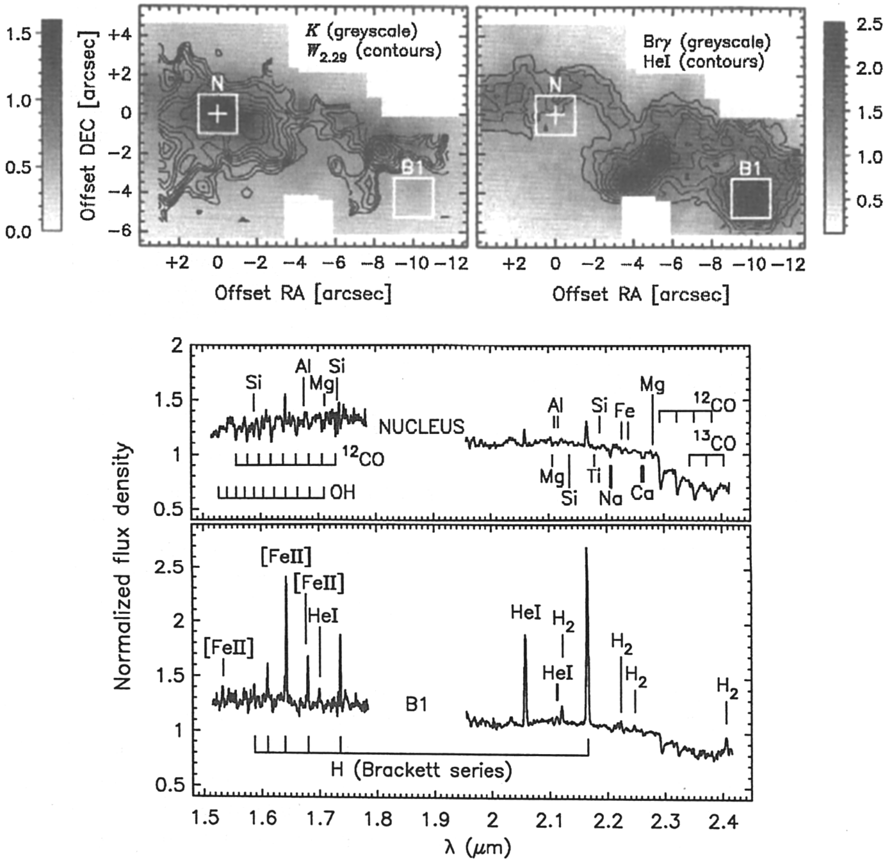

Figure 1. 3D maps of M 82 and spectra of the nucleus (cross, 'N') and region 'B1'. Greyscale levels are in $10^{-14}\,\mathrm{W\,m^{-2}\,\mu m^{-1}\,arcsec^{-2}}$ for the K-band map and $10^{-17}\,\mathrm{W\,m^{-2}\,arcsec^{-2}}$ for the Brγ map. Contours for the $W_{2.29}$ map range from 12 Å to 16 Å in steps of 0.5 Å, those for the He I 2.058 μm linemap range from 0.5 to 1.5 in steps of 0.1 and units of $10^{-17}\,\mathrm{W\,m^{-2}\,arcsec^{-2}}$. The spectra are normalized to unity in the range 2.2875 - 2.2910 μm (normalizing factors in $10^{-14}\,\mathrm{W\,m^{-2}\mu m^{-1}}$ are 6.52 for the nucleus and 1.78 for B1).

Among the key diagnostics provided by the 3D and SWS data, we used H and He recombination lines and mid-infrared fine-structure lines of Ne, Ar, and S originating in H II regions to constrain the properties of the most massive stars present. We also used the equivalent widths of near-infrared stellar absorption features including the CO 2.29 μm and 1.62 μm bandheads ($W_{2.29}$, $W_{1.62}$) to characterize the cool evolved star populations. Figure 1 presents selected 3D maps together with the H- and K-band spectra of the central 35 pc at the nucleus and of the brightest Brγ source $\sim 10''$ to the southwest ('B1').

The maps show distinct burst sites on scales as small as 25 pc and important spatial variations in the strength of the absorption features and emission lines relative to the continuum. The distribution of CO bandhead equivalent widths follows well the H- and K-band emission. Comparison of the $W_{2.29}$

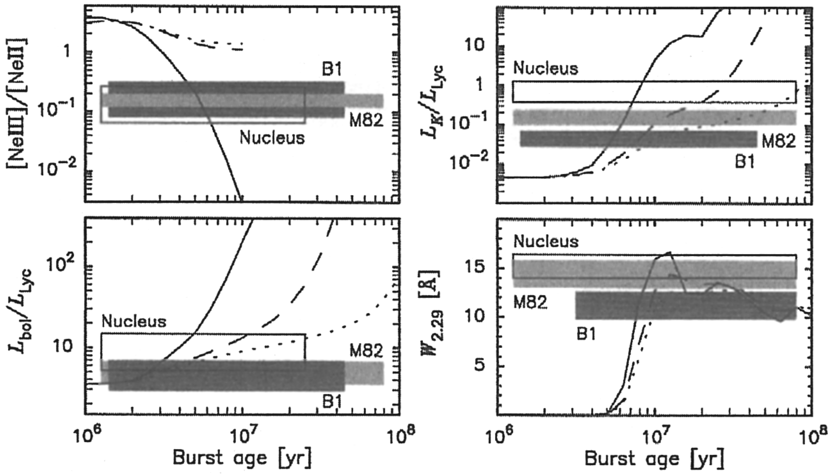

Figure 2. Comparison of the properties of selected regions in M 82 with model predictions for a Salpeter IMF between 1 and 100 $M_\odot$ and burst decay timescales of 1, 5, and 20 Myr (solid, dashed, and dotted curves). Measurements for the starburst core ('M 82'), the nucleus, and the Brγ source B1 are indicated by horizontal bars of width corresponding to the uncertainties.

and $W_{1.62}$ with empirical stellar data (*e.g.*, Origlia, Moorwood & Oliva 1993; Förster Schreiber 2000) together with the mass-to-K-band light ratio (M/L_K) indicate that red supergiants of temperatures 3 600 - 4 500 K dominate the near-infrared continuum, with the cooler stars located at the nucleus and along a ridge extending up to just north of B1. The distribution of the ionized gas line emission contrasts sharply with that of the red supergiants light, with very little emission at the nucleus, prominent sources to the west, and little variation in the ratios of He to H recombination lines. From photoionization modeling using CLOUDY (Ferland 1996) and the non-LTE unified stellar atmospheres of Pauldrach, Hoffmann & Lennon (2001), the nebular line ratios (*e.g.*, He I 2.058 μm/Brγ, [Ne III] 15.6 μm/[Ne II] 12.8 μm) imply temperatures of $\sim$ 37 100 K for the OB stars with small dispersion of 650 K, suggesting that stars of masses $\gtrsim$ 30 $M_\odot$ have disappeared due to rapid aging of the starburst.

3. Recent history of M 82: modeling the starburst core

In order to constrain quantitatively the star formation history in the regions observed, we applied starburst models which combine evolutionary synthesis and photoionization modeling with STARS and CLOUDY (Sternberg 1998; Ferland 1996), and employ the Geneva tracks (*e.g.*, Schaller *et al.* 1992) and the Pauldrach *et al.* (2001) atmospheres. Figure 2 compares the observational constraints for the nucleus, region B1, and the starburst core with model predictions. The Lyman continuum and bolometric luminosities (L_{Lyc} and L_{bol}) were derived from our H line fluxes and from the 12 μm data of Telesco & Gezari (1992), respectively. The models were computed for a Salpeter IMF $dN/dm \propto m^{-2.35}$

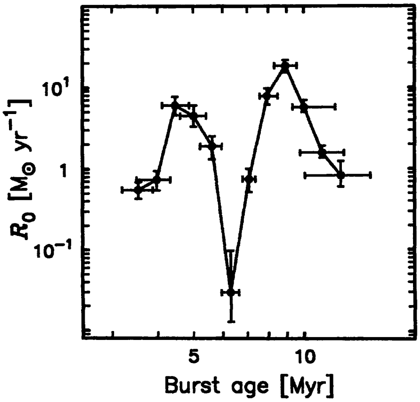

Figure 3. Star formation history in the central regions of M 82 reconstructed from the spatially-detailed modeling by integrating the burst intensity per age interval.

between 1 and 100 $M_\odot$ and various timescales t_{sc} for a star formation rate $R(t) = R_0 \exp(-t/t_{sc})$.

Focussing on the diagnostics tracing the OB stars, the Ne line and L_{bol}/L_{Lyc} ratios can only be reconciled with very short burst timescales of a few 10^6 yr at most and imply ages of 4 - 5 Myr. On the other hand, the strength of the 2.29 μm CO bandhead produced exclusively in the atmosphere of cool stars implies systematically older ages $\gtrsim$ 8 Myr and, for the nucleus, suggests $t_{sc} < 5$ Myr. We adopted the younger age solutions from $W_{2.29}$; the very low M/L_K ratio in the starburst core supports the presence of very young red supergiants throughout. The L_K/L_{Lyc} ratios probing both hot main sequence and cool evolved stars indicate intermediate ages.

The various constraints are difficult to reproduce simultaneously with single bursts of any timescale. Models consisting of two successive short bursts are more successful, with the younger burst accounting for the properties dominated by OB stars (neon ratio, L_{Lyc}, L_{bol}) and the older burst for those dominated by red supergiants (L_K and $W_{2.29}$). For regions a few tens of parsecs in size, very short burst timescales can be explained by stellar winds and supernova explosions rapidly disrupting the surrounding interstellar medium (ISM) after the onset of star formation. The spatial superposition of two distinct bursts towards individual regions can be attributed to projection effects. The red supergiants are distributed in the disk and concentrated around the nucleus while the H II regions lie mainly along a circumnuclear ring; given the nearly edge-on orientation of M 82, the corresponding burst populations contribute to the properties measured along each line of sight within the 3D field of view.

Assuming two successive short bursts ($t_{sc} = 1$ Myr), we modeled all individual resolution elements in our 3D data to constrain the burst age and intensity. The resulting star formation history, obtained by integrating the initial star formation rate R_0 per age bin, is plotted in Figure 3. Two distinct starburst episodes are outlined, each of duration of a few 10^6 yr, peaking 4.5 and 9 Myr ago. The spatial distributions of burst ages and intensities indicate a roughly constant age for each burst population, with the older burst having been particularly intense within 50 pc of the nucleus while the younger burst was concentrated at larger radii coinciding with the ring of ionized gas. The low M/L_K ratio and the presence of young supernova remnants further support lower level activity out to radii of $\sim$300 pc during the older episode. Our spatially detailed modeling suggests that each starburst episode in the central 500 pc of M 82 was triggered nearly simultaneously, presumably due to large gas inflows and brief compression events, and decayed substantially within a few 10^6 yr locally due to strong negative feedback effects, resulting in a similarly rapid decline of the global star formation activity.

4. Earlier history of M 82: the fossil starburst regions

Recently, de Grijs *et al.* (2001) investigated the properties of the compact luminous stellar clusters and individual bright giant stars resolved in optical and near-infrared *HST* imaging of a disk region $\sim$ 1 kpc northeast of the nucleus. The presence of an intermediate age population at this location has previously been inferred from optical spectroscopy (*e.g.*, Marcum & O'Connell 1996), showing high-order Balmer absorption lines and a prominent Balmer break. From evolutionary synthesis modeling, de Grijs *et al.* (2001) found cluster ages ranging from $\sim$30 Myr to over 10 Gyr and derived ages for the brightest giants of 20 - 30 Myr. The cluster age distribution reveals a peak around 650 Myr with full width of $\sim$ 500 Myr and very few clusters younger than 300 Myr, delineating an earlier "extranuclear" starburst episode of comparable amplitude as the recent ones in the starburst core.

5. Lessons from the starburst Rosetta Stone

Simple considerations of timescales allow us to link the starburst history of M 82 with possible mechanisms driving its evolution (as discussed in detail by de Grijs *et al.* 2001 and Förster Schreiber *et al.* 2002). Numerical simulations of the M 81/M 82/NGC 3077 group date the last close passage between M 82 and M 81 at $\sim$ 200 Myr ago (*e.g.*, Yun, Ho & Lo 1994; Yun 1999), close to the epoch of enhanced cluster formation in the fossil starburst regions. The orbital period at radii of 1 000, 500, and 85 pc is of $\sim$ 100, 20, and 5 Myr, corresponding fairly well to the 'outside-inside-out' propagation of the starburst episodes. Comparison of the cumulative mechanical energy injected into the ISM (derived from our models) and its gravitational binding energy suggests the collective effect of stellar winds and supernova explosions is able to disrupt the current gas reservoir in the central 500 pc on timescales of $\lesssim 10^6$ yr, supporting feedback effects as plausible efficient quenching mechanism for the two recent bursts.

The following scenario can be proposed for M 82: (*i*) As a result of the interaction with M 81 $\sim 10^8$ yr ago, the ISM in M 82 experienced strong large-scale torques, loss of angular momentum, and important infall towards the nuclear regions, leading to enhanced star formation activity in the central kiloparsec. The stellar bar, likely induced by the interaction, may have played a role in channeling the inflow; depending on the details of the bar development, the infalling ISM can reach the nucleus or be trapped in circumnuclear regions due to dynamical resonances; (*ii*) A first starburst episode took place 650 Myr ago at radii of ~1 kpc. Enhanced star formation in these regions subsided about 300 Myr ago and was suppressed in the last 20 - 30 Myr. Bar-related resonances and self-gravity may have prevented substantial dispersion of the burst site over the past several rotation periods; (*iii*) A starburst episode followed 8 - 15 Myr ago throughout the inner 500 pc and was rapidly exhausted. The central few tens of parsecs at the nucleus hosted the most intense star formation activity; and (*iv*) A subsequent episode 4 - 6 Myr ago was triggered predominantly by bar-induced resonances, taking place mainly in a circumnuclear ring of radius ~85 pc and further out along the bar, and also decayed rapidly.

A more complete picture of starburst activity in M 82 has emerged from the combination of results for both the active starburst core and the outer post-starburst disk regions, revealing its episodic behaviour and complex spatial progression. The case of M 82 emphasizes the importance of both detailed and global approaches for constraining the overall starburst history in galaxies, and the interplay between large-scale dynamical mechanisms and feedback processes determining the evolution of starburst activity.

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Discussion

LEITHERER: Can we hope to obtain near-IR spectra at $R \approx 10\,000$ to resolve the CO features in the H- and K-bands? The controversy on the low-mass end of the IMF is still unsettled and a virial mass determination could answer this question.

SCHREIBER: The issue of low-mass IMF in starbursts is indeed very crucial. In M 82, I am aware of one group working on this topic and trying to use NIRSPEC at the Keck Telescope to determine dynamical masses of clusters in the nuclear regions, but results have not been announced yet. I think it is difficult because of sensitivity limitations. Smith & Gallagher (1999, AAS 194, 1203) have studied cluster 'F' based on optical data, and conclude there might be indications for an IMF biased against the formation of low-mass stars, but this remains to be confirmed with improved data.

JOHNSON: Two comments. (*i*) Based on the radio data of Kronberg *et al.* (2000, ApJ 535, 706), there don't appear to be any compact thermal radio sources (we may not be able to disentangle them from all the non-thermal emission). If there really aren't any, this implies that star-formation is currently shut off and perhaps we are seeing some kind of regulation mechanism which is very interesting. (*ii*) This comment is really for all of the speakers this afternoon. I think we need to be very careful about what we call a 'super' star cluster, so that we aren't calling objects 'super' which are really just very impressive.

SCHREIBER: (*i*) These results are consistent with our findings from the modeling, that support very short timescales for the most recent starburst episodes in the central 500 pc of M 82 of about a few million years only. The last burst peaked at about 5 Myr ago and has declined very rapidly in intensity, with little of any current star formation still on-going. (*ii*) Masses inferred for the clusters resolved with *HST*-WFPC2 in M 82 range from $\sim 10^4$ to $\sim 10^6\,M_\odot$. The $\sim 10^6\,M_\odot$ clusters can be called 'super', but I suppose at the lower range, it becomes less clear and a matter of personal choice in definition. I agree that a consensus in definition should be established.

STEVENS: What are the relative (absolute) sizes of the two recent burst in M 82?

SCHREIBER: The two most recent bursts in the starburst core of M 82 (central 500 pc) were of comparable intensity in terms of mass of stars formed. Assuming two exponentially decaying bursts with a timescale of 1 Myr, the older burst (~ 10 Myr) produced a factor of 2 - 4 more mass than the younger burst (~ 5 Myr). Absolute masses are dependent on the assumed lower mass cutoff of the IMF. For a Salpeter IMF from $1\,M_\odot$ to $100\,M_\odot$, we find about $4\times10^7\,M_\odot$ and $1.6\times10^8\,M_\odot$ for the youngest and oldest bursts, respectively, within the starburst core.