Spatially Resolved Spectroscopy of Super Star Clusters in the M82 Starbursts

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Abstract

M82 is the prototype starburst galaxy and the nearest analogue to the star forming galaxies recently identified at high redshifts. There is good evidence that M82 has experienced multiple starburst episodes over the past $\sim$ 800 Myr. No other galaxy affords the opportunity to study both an active starburst and the subsequent post-burst phase at such close range (3.6 Mpc) and with such a wealth of complementary data from other space and ground-based telescopes. In our Cycle 1 and 7 HST imaging programs on M82, we identified numerous super star clusters, which seem to be hallmarks of intense star formation. We propose to obtain spatially-resolved STIS spectroscopy of 20 such clusters in M82's active starburst core and also in its "fossil" starburst region (of age $\gtrsim$ 200 Myr) as a means of tracing the history of star formation and its propagation. With the spatially-resolved spectra, we will be able to study the internal structure of the clusters, evidence for internal mass segregation, their interaction with their surroundings (including M82's superwind), and the character of the bright, diffuse non-cluster populations.

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Total number of investigators: 4
Number of ESA investigators: 2 (indicated by * after name)

Observing Summary:

Target	RA	DEC	V	Configuration,mode,aperture spectral elements	Total orbits	Flags
M82-A-POS1	09 55 53.44	+69 40 50.5	12.6	STIS/CCD ACCUM G430L,G750M(6768,8561),[52X0.1]	4	
M82-A-POS2	09 55 53.17	+69 40 50.6	12.6	STIS/CCD ACCUM G430L,G750M(6768,8561),[52X0.1]	4	
M82-B1-CLUS1+2	09 56 03.30	+69 41 11.7	17.9	STIS/CCD ACCUM G430L,G750M(6768,8561),[52X0.1]	4	
M82-B2-CLUS1+3	09 55 54.49	+69 41 01.1	17.9	STIS/CCD ACCUM G430L,G750M(6768,8561),[52X0.1]	4	
M82-F+L	09 55 50.96	+69 40 39.7	15.8	STIS/CCD ACCUM G430L,G750M(6768,8561),[52X0.1]	4	
				Grand total orbit request	20	

Scientific Justification

1 M82 as a Starburst and Post-Starburst Template

M82 is the nearest and best-studied starburst galaxy. Observations at all wavelengths from radio to X-rays (reviewed in [36] [31]) are consistent with the following scenario: During the last several 100 Myr years, tidal interactions with M81 induced an intense starburst in M82 with a star formation rate of ~ 10 $M_\odot$ yr^{-1}. Energy and gas ejection from supernovae, at a rate of ~ 0.1 supernova yr^{-1} [28] [30], drive a large-scale galactic wind along the minor axis of M82 (e.g., [21] [23] [34]). All of the bright radio and infrared sources associated with the active starburst are confined within a radius of ~ 250 pc of the galaxy's center. Most of this volume is heavily obscured by dust at optical wavelengths.

However, the outermost parts of the starburst core have lower extinction and can be studied with optical telescopes. *HST V* and *I*-band imaging of bright optical features in the direction of the core (labeled M82 A, C, and E in the nomenclature of [28]) revealed over one hundred young "super star clusters" with $M_V \sim -12$, brighter than any star cluster in the Local Group [27]. Ages of these clusters, and those lying deeper within the dusty core, are estimated to be ~ 10 Myr [28] [32].

There is now ample evidence that this was not the only major starburst episode to have occurred in M82. Two regions at ~400-1000 pc NE of the center, M82 B1/B2, have the high surface brightness and A-star dominated absorption line spectrum expected for a fossil starburst with an age $\gtrsim 100$ Myr and an amplitude similar to the active burst [28] [22]. In *HST* Cycle 7, we obtained *WFPC2-PC* and *NICMOS* images of regions B1 and B2 and detected another ~ 150 compact super star clusters with intrinsic luminosities of $M_V \gtrsim -9$ [7]. Using broad-band *BVIJH* colors [7] and Hα images [6], we estimated ages for these of 200–2000 Myr, with a peak near 500 Myr. The clusters have radii between 3 and 8 pc, consistent with Galactic globular cluster sizes. Gallagher & Smith recently obtained an age of 60 Myr for the very luminous ($M_V \sim -16$) cluster F, located 440 pc SW of the galaxy's center [10]. These results suggest that starburst activity in M82 is of longer duration than had been supposed and has propagated through the galaxy's disk. Infrared data on the starburst core likewise suggest internal propagation there [32].

<u>*General Importance to Astronomy:*</u> The significance of M82 and the project proposed here lies in the broader context of galaxy evolution. Starbursts of this scale are likely to be common features of early galaxy evolution, and M82 is the nearest analogue to the intriguing sample of star-forming galaxies recently identified (e.g. by their Lyman dropouts) at high redshifts ($z \gtrsim 3$) [35] [11] [20]. M82 affords a close-up view not only of an active starburst but also, in region B, of the subsequent post-burst phase which is apparently responsible for the unusual "E+A" or "quenched" spectra which are frequently encountered in Butcher-Oemler effect galaxy clusters at high redshift [29] [9] [5]. Other nearby galaxies are known to exhibit one or another of these features, but *none of these offers the opportunity to study both at such close range (3.6 Mpc), or with such a wealth of correlative data, as does M82.*

2 Spectroscopy of Super Star Clusters in M82

Production of luminous, compact star clusters such as those described above seems to be a hallmark of intense star formation episodes. They have been identified (mostly with *HST*) in several dozen galaxies, often involved in interactions (e.g., [16] [40] [26] [4] [39] [2]). Their sizes, luminosities, and masses are entirely consistent with what is expected for young globular clusters [24] [38] [15] [14] [33]. Super star clusters are therefore important because of what they can tell us about globular cluster formation and evolution (e.g. destruction mechanisms and efficiencies). They are also important as probes of the history of star formation, chemical evolution, initial mass function, and other physical characteristics in starbursts. This is so because each cluster approximates a coveal, single-metallicity, simple stellar population. Such systems are the simplest to model, and their ages and metallicities and, in some cases, initial mass functions can be estimated from their integrated spectra.

We propose to study the stellar populations and gas flows in and near a sample of M82 super star clusters using the the excellent spatial resolution and long-slit capability of STIS. We will include 6 individual super star clusters and the M82 A cluster complex, covering the range of star-forming epochs identified to date. In each separate pointing, we will orient the slit position angle so that more than one target is included. The individual cluster sample will include 2 clusters from region B1 ($r = 1000$ pc, age $\gtrsim 200$ Myr), 2 clusters from region B2 ($r = 500$ pc, age $\sim$ 50-500 Myr), and the two clusters F and L ($r = 400$ pc, age $\sim$ 60 Myr); here r is the projected distance from the starburst core.

Region A is of special interest. It is a remarkable complex of super star clusters and bright diffuse populations (see Fig. 1), with very high continuum [28] [27] and emission line [18] [23] surface brightnesses. The whole starburst core of M82 is likely to be pervaded by clusters similar to those in A. The visible clusters offer an outstanding opportunity for analysis of the stellar population and gas-dynamical properties which characterize starbursts. To sample its internal structure, we will make two observations of A, each with the slit oriented along the major axis of the $10''$-long cluster complex, including 5-8 clusters in a single exposure (see Fig. 1). Our total sample will therefore include about 15-20 clusters.

The specific scientific issues we want to address for our cluster sample are the following:

(i) We will determine better ages and metallicities for each cluster from our absorption line spectra so as to examine the pattern of formation times across the face of the galaxy and the evidence for propagating star formation. Based on previous experience, we anticipate to be able to determine the clusters' ages with a formal accuracy of better than 30%. The presence of the Balmer jump is required to determine reliable ages [8], since the SSCs tend to be dominated in the blue by B- or A-type spectra [1] [33]. The well-known "age-metallicity" degeneracy is a less serious issue for objects with ages < 1000 Myr than for older ones (e.g. [39]). More details on our spectral analysis techniques are given in the Observations section.

(ii) We will determine if there are internal gradients in the spectral signature within clusters in our spatially resolved data which may be related to multiple star forming events

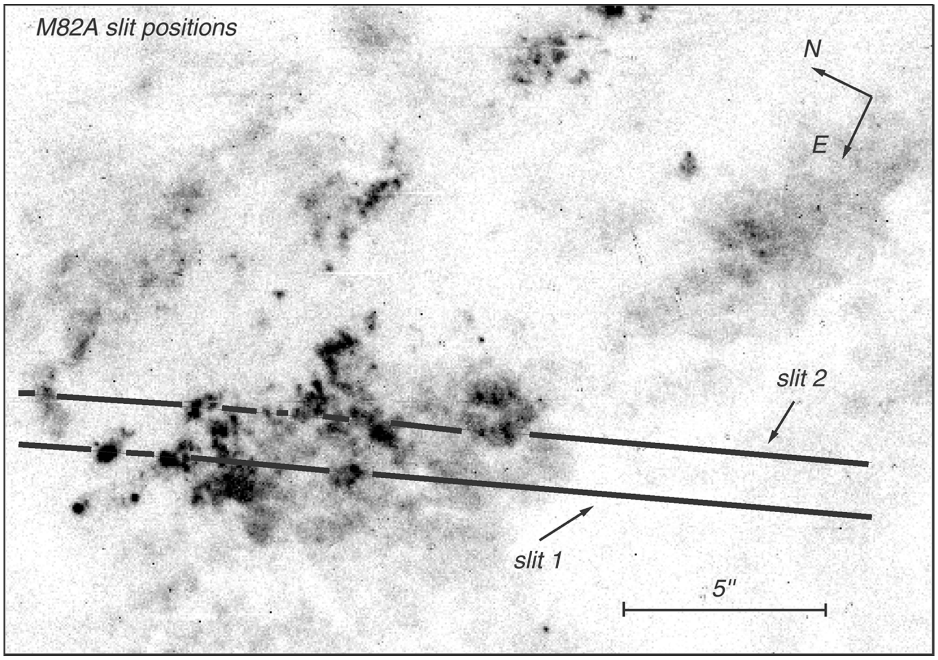

Figure 1: WFPC-2 V-band image of the center of M82 showing the M82 A complex of super star clusters. Two possible positions for the STIS slit are shown. The total slit length extends outside the frame.

[12] or mass segregation within the clusters. Sinking of the most massive and luminous stars towards the center (as is observed in R136 in 30 Dor) can bias measured velocity dispersions, and derived masses, to lower values. Masses, in turn, are important in deciding whether the clusters are truly proto-globulars. We will not be able to measure velocity dispersions with our STIS data, but LS and JSG have recently measured a value of $\sigma = 13.2$ km s^{-1} for M82 F with high dispersion spectroscopy from the ground.

(iii) The long slit will provide excellent sampling of the unusually bright diffuse light in M82. As seems typical in starbursts, clusters contribute only $\sim 20\%$ of the total light [25]. The diffuse population might consist of dissolved clusters or it may have formed *in situ*. Spectral analysis of the diffuse light and its spatial dependence will help distinguish these possibilities and clarify star formation processes in starbursts.

(iv) The morphology and ground-based kinematics of region A and the base of the galaxy's gas plume suggest that these clusters are the source of some of the hot gas and energy driving the superwind in M82 [27] [28]. Our emission line spectra will probe, on scales of ~ 2 pc, what we anticipate will be a complex transition region between the clusters and the base of the wind and can test predictions of models for galactic superwinds (e.g., [3]), such as the expected gas transfer rate, gas pressure, and energy input needed for the supernova-induced driving force.

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Description of the Observations

1 Need for HST

This program could not be carried out with ground-based spectrographs for two reasons. First, an important goal is to study gradients and differential characteristics within and near our targets, most of which show evidence of structure on $0.1''$ (1.8 pc) scales. The full-width-half-maxima of most of our targets are $\sim 0.3 - 0.4''$. Ground-based spectra are already available for clusters F and L [10]; however the poor spatial resolution prevented study of their internal structure. Region A is yet more complex and highly structured than these individual clusters (Fig. 1).

Second, the targets are superposed on very bright backgrounds. Both regions A and B have background surface brightnesses $\mu(V) \sim$17–18 mag arcsec^{-2}, and ground-based seeing ($\gtrsim 0.5''$) would cause serious contamination of the data. Simulations of the effects of ground-based seeing using our HST images show that the bright, highly variable background would significantly affect ground-based spectroscopy, even of the brightest sources in the field. Quantitatively, the net effect on the brightest sources in the M82 B field is to produce $\sim 40\%$ contamination by background light. The effects on the fainter clusters are yet more serious.

2 Spectroscopy, CVZ Utilization, & Exposure Estimates

We have good astrometry for all targets from HST and ground-based data. We will orient the spectrograph slit to pick up at least two targets of interest in each pointing (and up to 8 in region A). In most cases, the two targets are separated by less than $6''$. Figure 1 shows two possible slit settings for our region A samples. Because of the consequent ORIENT requirements, we cannot (according to §4.1 in the Call for Proposals) take advantage of the fact that M82 lies in the Continuous Viewing Zone (CVZ).

We plan to use the $52'' \times 0.1''$ slit on the clusters, with a resolution of 1.8 pc in M82 perpendicular to the dispersion direction. This takes nearly full advantage of *HST*'s spatial resolution and yields the spectral resolution (5.4 Å for extended sources) in the blue which is necessary to perform good spectral synthesis on absorption line spectra. Three grating settings will be used: G430L to cover the blue spectral region from 3000 to 5700 Å (primarily absorption lines and the Balmer jump); G750M centered at 6768 Å to cover the Hα-[N II]-[S II] emission line region; and G750M centered at 8561 Å to cover the infrared Ca II triplet and Paschen absorption lines. Spectral resolution for the two G750M settings will be 1.1 Å.

For exposure estimates with the STIS Exposure Time Calculator we used sizes and V or I-band fluxes taken from our *WFPC2* images. We treat the clusters as extended sources with characteristic diameters of $0.3''$. Based on the colors, we adopted for the region B1 and B2 clusters spectral energy distributions corresponding to a 500 Myr-old population. For

F and L, we adopted 60 Myr [10]. For region A, we adopted 10 Myr. Adopted extinction values (A_V, mags) were 0.6, 4.0, and 2.2, respectively [10] [22].

Our S/N requirements are driven by our experience with spectral synthesis techniques. We require a mean S/N of $\sim 25 - 40$ per spectral resolution element for 3800–4800Å and lower values ~ 10 in the red. We find that the blue G430L spectra will require 5400 sec (2 orbits) of integration but that 2700 sec (1 orbit) will suffice for each G750M setting. Therefore, 4 orbits are needed per cluster pointing, including overhead.

3 Spectral Synthesis & Emission Line Analysis

To estimate ages and metallicities for the star clusters, we will use spectral synthesis techniques like those described in [22] and [10], in which optimized fits of theoretical model cluster spectra are made to the data. Spectroscopic values will be considerably more reliable than the available crude estimates based on broad-band colors. Our earlier experience with these methods suggests that a formal age uncertainty of about 30% will be typical. Dating reliability is strongly affected by S/N, spectral resolution, and wavelength coverage—which have therefore shaped our observing requirements. The most serious difficulty is dust reddening of the clusters, which varies from place to place within M82. Age estimates can be made in the presence of large reddening as long as the spectra contain strong spectral features. For this reason, the blue region 3500-5500 Å, which includes the Balmer jump, the higher Balmer absorption lines, He I, Ca II, and several other metallic features in systems with ages 10-1000 Myr is of critical importance. The Ca II infrared triplet (8500-8700 Å) is an important signature of evolved supergiants and luminous giants and provides additional age constraints [10]. It will be especially useful for the more heavily reddened objects.

Age dating of very young clusters (< 10 Myr), which are probably present within the M82 A complex, could be better done at far-UV wavelengths (e.g. [19]), but this is precluded for M82 because of the extinction. However, our spectra should distinguish < 10 Myr-old clusters from older ones. The signatures of ~ 5 Myr-old Wolf Rayet stars might be present in some cases in the characteristic broad feature centered on He II 4686 Å. We will examine our spectra for evidence of anomalies, such as those claimed in NGC 1275, which might be related to initial mass functions which are abnormally flat or truncated [1].

The well-known "age-metallicity" degeneracy is a less serious issue for objects with ages < 1000 Myr than for older ones. However, by the same token, our spectra will provide only fair limits on stellar metallicity. With data of this quality, metallticies can be determined within about ± 0.15 dex [33].

In sources without line emission, the G750M/6768 spectra will yield additional constraints on ages through Hα absorption line strengths. Where line emission is present (e.g., region A), we will obtain $0.1''$ resolution kinematical profiles with ~ 5 km s^{-1} velocity resolution. These provide information about line-of-sight distributions of material within the galaxy [10], the character of intra-cluster and external gas flows, and possibly cluster masses

[28]. The presence of strong [S II] is a signature of shock waves.

Special Requirements

Coordinated Observations

Justify Duplications

Previous HST Programs

GO-2389: AJ, 108, 84, 1994; ApJ, 433, 65, 1994; ApJ, 446, L1, 1995

GO-2607: Nature, 364, 213, 1993; AJ, 108, 1567, 1994; AJ, 108, 1579, 1994; AJ, 108, 1598, 1994; ApJ, 460, 214, 1996.

GO-3545: in "Frontiers of Space and Ground-Based Astronomy", eds. E.W. Wamsteker, M.S. Longair, and Y. Kondo (Dordrecht: Kluwer), p. 663, 1994.

GO-6423: paper in press (see below)

GO-6585: AJ, 116, 2297, 1998

GO-6053/7732: FOS/STIS spectroscopy delayed by safing events and NICMOS campaign. ApJ, 530, 352, 2000

GO-7438: Long-slit STIS spectroscopy, delayed by NICMOS campaign, now complete and being analyzed. Paper on UV flare in nucleus of NGC 1399 in preparation.

GO-7446: Cycle 7 program to obtain WFPC2 and NICMOS images of the "fossil" starburst region in M82. Data reduced and analyzed. Star cluster candidates photometered in BVIJH, sizes measured, evolutionary status deduced from multi-color correlations. Publications listed below. This proposal based largely on results from GO-7446.

AR-8358: census of hot HB and post-HB stars in globular clusters. In progress.

GO-8643: far-UV photometry of M87 globular clusters. Awaiting observations.

GO-8645: Windhorst, R.A., et al. (incl. de Grijs, Gallagher, O'Connell). Observations in progress, reduction and analysis have been started.

HST Publications Related to this Program:

de Grijs, R., O'Connell, R.W., Gallagher, J.S., 2000, "The Fossil Starburst in M82," submitted to AJ

Hunter, D.A., O'Connell, R.W., Gallagher, J.S., & Smecker-Hane, T.A., 2000, "The Star Clusters in the Starburst Irregular Galaxy NGC 1569, " AJ, in press

de Grijs, R., O'Connell, R.W., Gallagher, J.S., 2000, "The Fossil Starburst in M82," in: "The Evolution of Galaxies on Cosmological Timescales," eds. Beckman, J.E., Mahoney, T.J., in press

de Grijs, R., O'Connell, R.W., Gallagher, J.S., 2000, "Evolved Super Star Clusters in M82," in: "Star Formation from the Small to the Large Scale," 33rd ESLAB symposium, ESA SP-445, Favata, F., Kaas, A.A., Wilson, A., eds., in press

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