Compact radio sources in the spiral galaxy M83

Significance and immediate objectives

Understanding how stars are born and die is a fundamental problem of astrophysics. We are doing a comprehensive, multiband study of the stellar life cycle in the grand-design spiral galaxy M 83, one of the most actively star-forming systems in the local Universe. We have already obtained exceptional optical coverage with *HST*/WFC3 (Dopita et al. 2010) and Magellan/IMACS, and we have been awarded 750 ks of *Chandra* time for the X-ray observations, which will be carried out between 2010 Dec and 2011 Aug. Now we propose an ATCA radio study, crucial for integrating the optical and X-ray studies.

The radio study will allow us to achieve three **main objectives**:

a) monitor the long-term evolution of three *historical supernovae* (SNe) observed in M 83 over the last 100 years, and hence constrain the late stages of evolution of their stellar progenitors;

b) determine the distribution, radio spectral index and other physical properties of different types of *young supernova remnants* (SNRs), combined with their optical and X-ray properties;

c) resolve the morphology and search for variability of the *nuclear sources*: in particular, we will investigate the radio evidence for a double nucleus.

In addition, we will study the aligned triple source just outside the nucleus: the traditional interpretation is that it is a background radio galaxy, but it has recently been suggested that it could be a recoiling nuclear black hole (BH).

Supernovae and Supernova remnants in M83

Why M 83. M 83 (NGC 5236, SAB(s)c) has properties that make it uniquely important for a combined radio, optical and X-ray study of star-formation and compact remnants. It contains well-defined spiral arms with abundant star formation and hot gas, and a starburst nucleus with a large population of young, massive star clusters (Fig. 1). It is viewed nearly face-on ($i \approx 24^\circ$), and is sufficiently nearby ($d \approx 4.5$ Mpc, $1'' \approx 22$ pc) that we can probe several classes of discrete X-ray sources (X-ray binaries in the high and low state, SNRs, supersoft sources), identify their optical counterparts and spatially resolve SNRs. M 83 is the closest metal-rich galaxy ($Z/Z_\odot \gtrsim 2$), making it an important test of stellar and compact remnant evolution, in comparison to low-metallicity starbursts.

Historical SNe. M 83 is an excellent laboratory to study the transition of decades-old SNe into SNRs; this is a crucial phase for which we still have very little data (Immler & Kuntz 2005). Six historical SNe (very likely core-collapse SNe) have been seen in M 83 over the last 100 years. Previous radio studies with the VLA in 1983–1984, 1990 and 1998 (Stockdale et al. 2006, Maddox et al. 2006) have detected four of them: 1923A, 1950B, 1957D, 1983N. The last one faded very quickly after its discovery, but 1923A, 1950B and 1957D were still visible in 1998. By following their evolution a decade later, we will constrain the density of the circumstellar medium at larger and larger distances from the progenitor, as the shock wave expands into the stellar wind, before reaching the undisturbed ISM. This allows us to rewind the tape of the last phases of evolution of the progenitor, and infer the mass loss rate in its late stages. We will interpret their evolution using the radio SN models of Weiler et al.(1986,2002).

A new radio measurement of 1923A, 1950B and 1957D is very timely because we will also detect or strongly constrain their X-ray counterparts with our *Chandra* observations (down to $\approx 2 \times 10^{35}$ erg s^{-1} for a thermal spectrum). The X-ray luminosity provides an independent constraint on mass loss rate and wind velocity (Immler & Lewin 2003). So, it is crucial to have radio and X-ray data at the same epoch. Moreover, our proposed ATCA observation will go a factor of 10 deeper than the archival VLA data, and will provide a map at 3 cm (not observed with the VLA).

Young SNRs. Based on the observed SN rate and star-formation rate, we expect ~ 180 SNRs with age $\lesssim 3000$ yrs and ~ 600 younger than $10,000$ yrs. The majority will be core-collapse remnants. We want to identify and study the emission properties of a large fraction of them, with our combined radio/optical/X-ray study.

Radio, optical and X-ray searches are complementary (Blair & Long 2004; Pannuti et al. 2007). Narrow-band optical imaging identifies ISM-dominated SNRs from their high [SII]/Hα ratio, and ejecta-dominated SNR from their [OIII]/Hα ratio; but those techniques do not work well in optically crowded fields. In contrast, radio searches are more successful in crowded fields; the radio spectral index distinguishes between non-thermal (steep spectrum) SNR emission and thermal (flat spectrum) emission from HII regions. From radio data alone, radio SNRs may be confused with background AGN: but in most cases they will be distinguished from their optical and X-ray counterparts: X-ray SNRs have a soft thermal spectrum, while AGN have power-law spectra.

We have already obtained intriguing preliminary results from optical/X-ray data. We have identified more than 100 new SNRs in our Magellan images; including also those identified in the HST images (Fig. 2, left; Dopita et al. 2010), we now have more than 200 SNRs and SNR candidates. Thirty-four of those are probably young ($\lesssim 2000$ yr), and several appear to be ejecta-dominated. (Winkler et al., in prep.). Twenty-seven of the 34 young SNRs coincide with point-like X-ray sources in a 50-ks *Chandra* observation (Soria & Wu 2003). Our new *Chandra* observations will go an order of magnitude deeper: we expect to find ≈ 100 X-ray SNRs. We will also propose to extend the *HST*/WFC3 coverage of M 83 to match the *Chandra* field in the next observing cycle. With our ATCA program, we will measure the radio luminosities of the young SNRs, and will do the first systematic characterization and population study of this class.

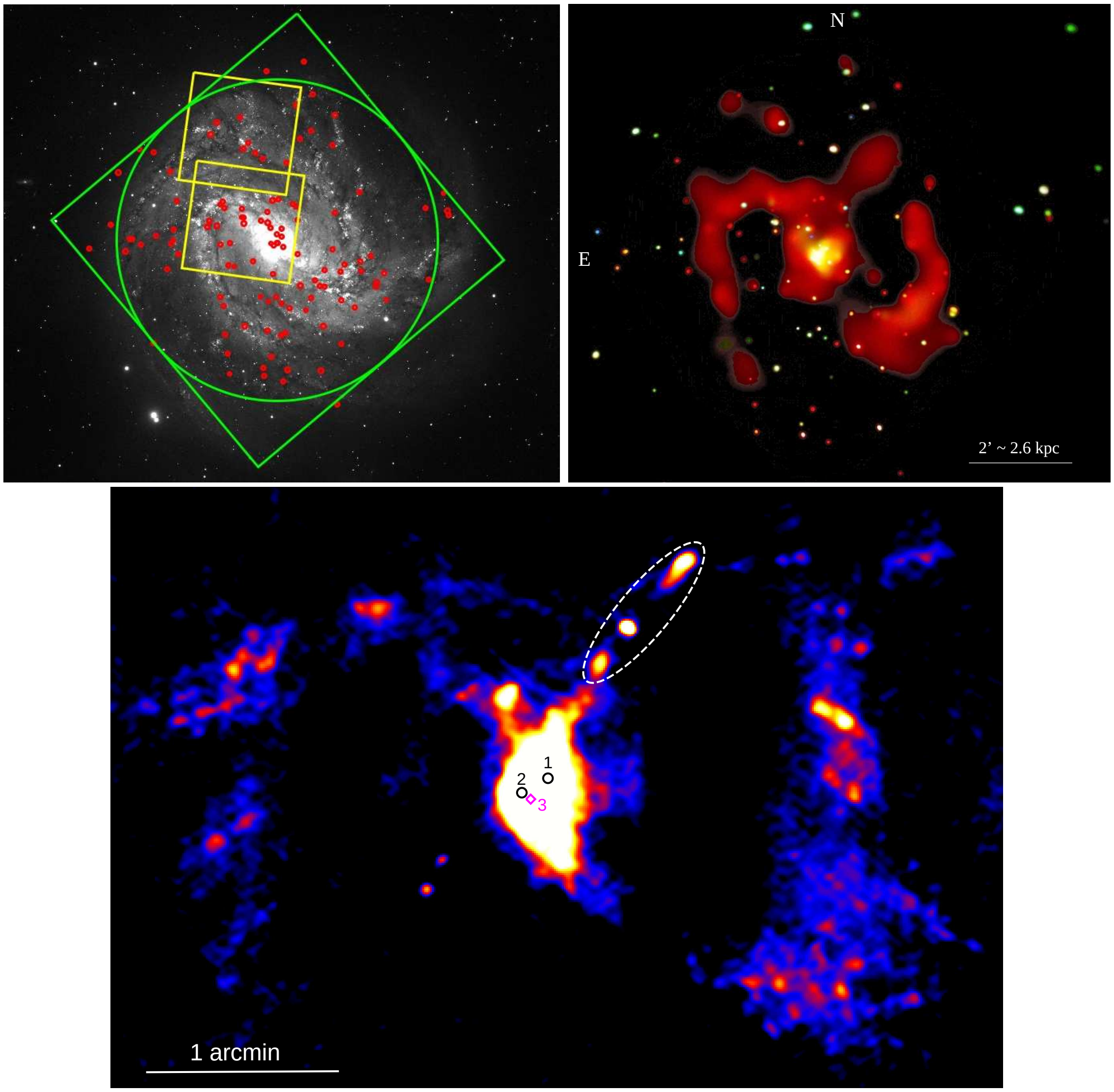

Figure 1: **Top left panel:** greyscale Hα Magellan image with the location of our *Chandra* and *HST* fields (green and yellow boxes, respectively); the red circles are the X-ray sources from Soria & Wu (2003). **Top right panel:** *Chandra*/ACIS X-ray colour image of M 83, from Soria & Wu (2003). Red: 0.3–1.0 keV; green: 1.0–2.0 keV; blue: 2.0–8.0 keV. **Bottom panel:** unpublished 6-cm radio map, which we obtained by combining the 1984 and 1990 VLA data. The circle marked as "1" is the radio nucleus; the one marked as "2" is the X-ray/UV nucleus (possibly the secondary nucleus); "3" is the dynamical and isophotal centre. The dashed ellipse identifies an intriguing triple source, which is interpreted either as a background radio galaxy, or as a powerful off-nuclear BH in M 83.

Recently, Chomiuk & Wilcots (2009) have argued that radio SNRs have a universal luminosity function, with a normalization proportional to the star formation rate in a galaxy but independent of ISM density. To test their model, we need large, well-studied samples in nearby galaxies; M 83 provides the ideal environment. From the VLA maps, Maddox et al. (2006) found 17 candidate radio SNRs, about half of which are also detected at optical and/or X-ray wavelengths. The ATCA maps will be a full order of magnitude deeper. If the Chomiuk & Wilcots model is correct, we predict that we will find ~ 100 candidate radio SNRs. We will then compare the radio and X-ray SNR luminosity functions, in regions of higher and lower ISM density (arms and interarm regions).

Pulsar wind nebulae. These are a subclass of young SNRs, where the radio emission comes from the pulsar wind. The Crab nebula is the most famous example. Radio searches can detect these young pulsars, but may not be able to distinguish them from compact HII regions, because their radio spectral index is flat. However, we will break the degeneracy with our *Chandra* and optical data. As an example, if located in M 83, the Crab would have a flux density of ≈ 0.1 mJy at 6 cm; the Large Magellanic Cloud's pulsar wind nebula 0540-69.3 would have a flux ≈ 0.05 mJy; they would both be detected in our ATCA study. In the X-rays, pulsar wind nebulae have characteristic luminosities $\sim 10^{36}$–10^{37} erg s^{-1}, so they will be identified in our *Chandra* study.

Resolving the nuclear structure

A double nucleus? The nuclear structure of M 83 is an unsolved problem, subject of active debate (Knapen et al. 2010, Muraoka et al. 2009, Fahti et al. 2008, Houghton & Thatte 2008, Maddox et al. 2006). The dynamical and

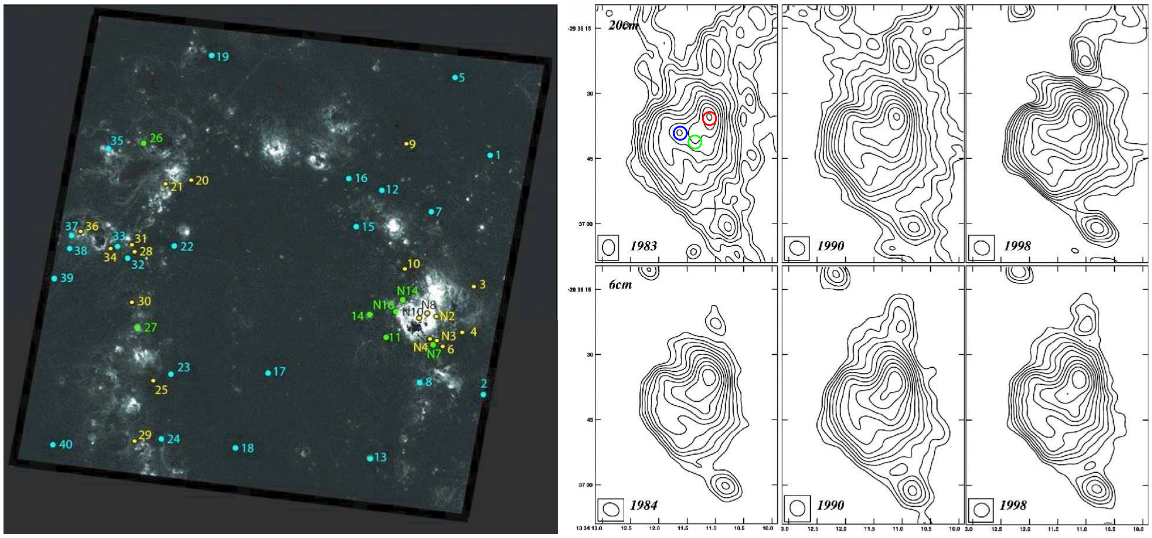

Figure 2: **Left panel:** *HST*/WFC3 Hα image of the eastern spiral arm (Dopita et al. 2010), highlighting M 83's extraordinary rich population of SNRs. The yellow points identify optical SNRs which we interpret as expanding in a high density medium; blue points are a physically different population of optical SNRs, expanding in a low density medium; green points are unclassified SNRs. **Right panel:** nuclear morphology in the VLA maps (Maddox et al. 2006). The red circle is the radio peak ($\approx$ 30 mJy beam^{-1} at 6 cm); the green circle is the X-ray/UV nucleus (a displaced nuclear BH?); the blue circle is the dynamical and isophotal centre of M 83 (an obscured nuclear BH?).

isophotal centre is unremarkable in most bands. The brightest X-ray/UV point-like source coincides with a massive star cluster, and is located $\approx 4''$ to the NE of the dynamical nucleus. The radio nuclear peak is offset from both (Fig. 2, right). A possible scenario is that there are two nuclear BHs: one currently active and moderately radiatively efficient; the other quiescent or jet dominated. Alternatively, there is only one nuclear BH, but it is offset from the dynamical centre because of a recent merger or interaction. We suggest that the main radio peak corresponds to the current peak of circumnuclear star formation; we will get a more accurate position and compare it with IR maps. Intriguingly, there are hints of secondary radio peaks near the other two nuclear positions (Maddox et al. 2006), which may trace the nuclear BH(s). We will resolve those peaks and perhaps other sources, with our improved sensitivity at 6 cm, and high spatial resolution at 3 cm. We will measure their spectral indices to distinguish thermal and non-thermal sources.

Background radio galaxy or off-nuclear BH? There is a very bright, triple radio source just outside the nuclear region (dashed ellipse in Fig. 1c). It is almost certainly a jet structure: unresolved core and extended lobes. The core is also an X-ray source. The conservative interpretation is that it is a background FR-II radio galaxy. Alternatively, it was recently suggested (Dottori et al. 2008, 2010) that it could be a recoiling nuclear BH or an intermediate-mass BH in M 83. We will measure the radio flux and spectral index of core and lobes, map the lobe structure and estimate the jet power. We will test a claim of lobe variability (Maddox et al. 2006), which would strongly disfavour the background AGN scenario. Combining the core radio and X-ray luminosities from the ATCA and from our new *Chandra* observations, we will estimate the BH mass in the fundamental plane of BH accretion (Merloni et al. 2003).

Proposed Observations and Feasibility

We propose to observe M 83 with a 6-km configuration, at 3 and 6 cm, for 3 sessions ($\approx$ 36 hr). At an RA = 13:37:00.79, Dec = −29:51:58.6, the galaxy is visible for $\approx$ 12 hrs a day at an elevation $> 20^\circ$. With 30 hrs on source, we will reach rms $\approx 5\ \mu$Jy/beam at 9 GHz, and $\approx 4\ \mu$Jy/beam at 5.5 GHz (uniform weighting). The corresponding beam sizes are $\approx 0.92'' \times 1.84''$ at 9 GHz, $\approx 1.5'' \times 3.0''$ at 5.5 GHz. Therefore, our map will be an order of magnitude deeper than the archival VLA maps at 6 cm (Table 1 in Maddox et al. 2006), with also a moderate improvement in the spatial resolution. We shall alternate observations of the target source and a phase calibrator. The primary flux density calibrator will be PKS B1934−638; the phase calibrator will be B1336-260.

Surprisingly, there are no recent 3+6cm ATCA observations of this iconic southern-sky galaxy. M 83 was observed with the 6-km configuration in 1991 (PI M. Dopita), then in 1993 with the 750-m and in 1996 with the 1.5-km configurations. We will use those archival data as additional datapoints for monitoring the evolution of the historical SNe; but a new observation in the CABB era would be very timely.

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