by Bill Blair and Frank Winkler

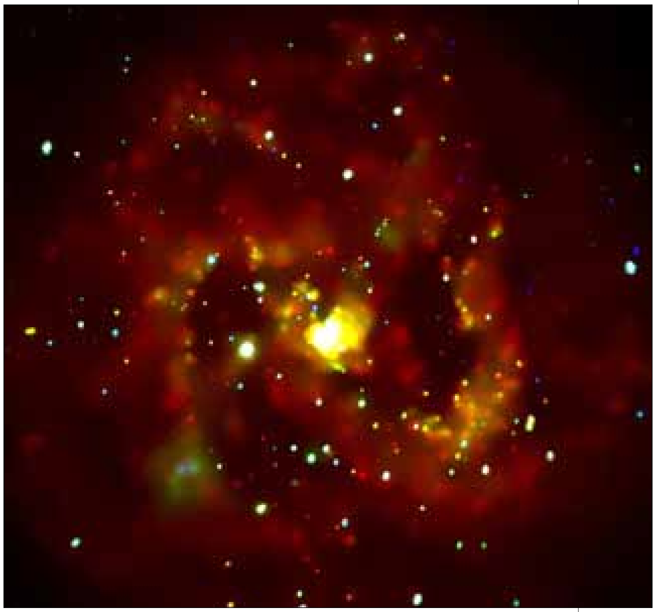
Constraining the Optical Counterpart of a New ULX in M83

Using the Gemini Multi-Object Spectrograph at Gemini South, an international team detected the optical counterpart to an ultraluminous X-ray source first detected by Chandra in late 2010. The authors, using Gemini in classical mode, received permission to re-prioritize their existing Gemini supernova remnant observations of M83. The results, which turned out to be a successful marriage of opportunity and serendipity, are presented here.

Figure 1.
M83 as imaged in April 2009 with the Magellan 6.5m telescope and IMACS instrument. Red is Halpha, green is [O III] 5007, and blue is B band.

Using multi-wavelength observations, we, along with several collaborators, are conducting an ongoing study of the cycle of stellar birth, evolution, and death to better understand how the interplay of these processes affects the evolution of entire galaxies. A particularly fruitful element of this study entails discovering and characterizing the supernova remnant populations in nearby galaxies. Recently, our team has concentrated on the iconic, face-on spiral galaxy M83 in the constellation Hydra (see Figure 1). Fortunately, the timing of this decision to study M83 was exquisite, as it led to the discovery of a most unusual optical counterpart to a bright X-ray transient source, the brightest X-ray point event in M83 by far. The nature of this source posed a puzzle that we are beginning to under-

Figure 2.
A color X-ray image of M83, from data obtained in 2010-2011 with the Chandra X-ray Observatory. Red represents soft X-rays (0.5 - 1 keV), green is medium (1 - 2 keV), and blue is harder X-rays (2 - 7 keV). The integration time totaled 729 ksec.



stand through a combination of observations from Gemini and the Hubble Space Telescope (HST), as well as the Chandra and Swift X-ray telescopes — plus some serendipity and a dose of good luck!

With a starburst nucleus and magnificent spiral arms — resplendent with star clusters, nebulae, and star-formation activity — M83 is a truly impressive galaxy. But this appearance belies its modest stature: the radius of M83's bright disk is less than half that of the Milky Way. Yet, with a distance of about 15 million light-years (ly), M83 lies close enough to allow detailed studies of its stellar and nebular properties (1 arcsecond corresponds to just under 72 ly at the distance of M83).

Despite its size, M83 is a "supernova factory," having generated at least six events since 1923. Until recently, M83 was tied with its northern counterpart, NGC 6946, as the most prolific producer of supernovae known, but, in the past few years, the latter galaxy has spawned a burst of three more and surged into the lead. Nonetheless, intense star formation and supernova activity must have been going on in M83 for quite some time, because the mean abundances in the gas-phase material appear to be well above solar throughout the galaxy's bright optical disk.

Thus, we selected M83, not only because of its proximity and favorable orientation, but especially due to its history of prolific star formation and destruction. In essence, by choosing M83 we have adopted a "Willie Sutton" approach; asked why he robbed banks, the notorious American bank robber Willie Sutton famously replied, "Because that's where the money is."

An X-ray Surprise

Over the last several years, we have undertaken a number of ground- and space-based programs on M83, including an April 2009 imaging study with the IMACS instrument on the 6.5-meter (m) Magellan I telescope (time assigned through the National Optical Astronomy Observatory Time Allocation Commmittee process), a 730 kilosecond exposure campaign from the Chandra X-ray Observatory (Principal Investigator Knox Long, Space Telescope Science Institute), and an April 2011 Gemini Multi-Object Spectrograph (GMOS) spectroscopy run at Gemini South.

Coming this summer, we will have a high-resolution imaging campaign with HST's Wide Field Camera 3 (WFC3), adding to some WFC3 data on M83 obtained in August 2009 as part of the post-Servicing Mission 4 Early Release Science (ERS) program. These various data sets, some still being obtained and analyzed, are beginning to pay off.

On December 23 and 26, 2010, our team received the data from the first of a long series of X-ray observations of M83 from Chandra. The first thing to pop out at us was a whopping bright X-ray point source where none had been seen before, about 1 arcminute east of the nucleus.

A quick calculation showed the source solidly among the ranks of the "ultraluminous X-ray source" (ULX) category, with $L_X = 5 \times 10^{39}$ ergs/

second. Like most compact X-ray sources, we believe ULXs derive their energy from the accretion of material from a more-or-less normal star onto a highly collapsed one (a neutron star or black hole).

What leads to classification as a ULX is a luminosity so high that its central engine must be a black hole with a mass larger than that of the most massive normal stars. (A simple relationship exists, known as the Eddington limit, which sets the maximum luminosity that can be sustained through normal accretion onto an object of a given mass; at a higher luminosity, the radiation pressure outward would exceed the gravitational attraction and choke off the accretion process.)

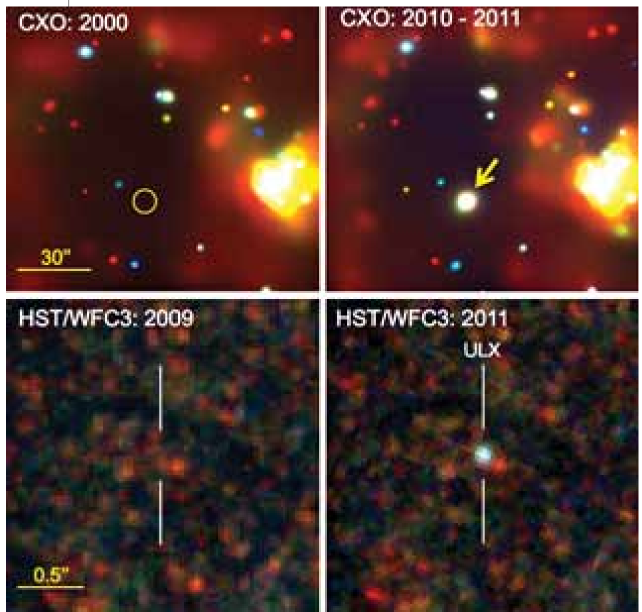


Figure 3. *Before and after outburst images in X-rays and in optical light (as viewed with HST/WFC3). The colors in the X-ray images are the same as Figure 2. The HST data show red (I band), green (V band), and blue (B band). The source corresponding to the ULX is obvious in the right hand panels. Note the scale changes from top to bottom panels.*

While we knew X-ray sources could vary in brightness from one observation to another, we didn't expect to see such a strong source present where none had appeared before. Again, this one easily shined as the brightest single source (out of over 250) in the entire galaxy! Calculating an upper limit from the earlier Chandra observation in 2000-2001, we determined that the source had brightened by at least a factor of 3000. Many previous X-ray missions (back to the 1970s) have targeted M83, but our searches of all the earlier data showed no evidence for any previous appearance of this source.

Chandra obtained the new data periodically over the entire calendar year of 2011, and we were also able to obtain Swift X-ray Telescope monitoring between some of the Chandra observations. From these we found that the new source varied somewhat in brightness and hardness ratio, but remained bright at least through the end of 2011.

The new ULX in M83 ranks among the closest such sources known — close enough, we thought, that it might be possible to see optical emission from the donor star providing the material that keeps the source glowing. This would give us some real physical insight into what's happening in the system. Through great fortune, HST had observed the field containing the source just 16 months earlier! However, pulling up those data revealed nothing at all unusual at the position of the X-ray source — just a few exceedingly faint red, low-mass stars of about 27th magnitude.

This discovery meant two things: 1) that the X-ray source had likely "turned on" sometime between August 2009 and December 2010, and; 2) that the normal, mass-donating star was an old, red star of relatively low mass. For most ULXs, if their galaxies are close enough for optical counterparts to be seen at all, the counterparts are very blue and thought to be much more massive (O or B) stellar companions to the black holes.

A Gemini Discovery

Another stroke of luck hit in April 2011, when we were scheduled to observe on the 8-m Gemini South telescope in Chile for a classical observing run. We intended to obtain GMOS spectra of M83 supernova remnants, following up on our earlier Magellan results. But with the Gemini Director's permission, we took advantage of GMOS's versatility to do direct imaging as well as spectroscopy, and to reprogram an hour of our observing time for broadband imaging of the region containing M83's new ULX.

When we compared these Gemini data to the April 2009 Magellan images, we discovered that a faint blue star had now appeared at the position of the X-ray source, with a visual magnitude of ~ 24! But did this source correspond with one of the faint red stars seen in the earlier HST data? Only new HST images would tell us that.

Knowing that an optical counterpart had appeared, our team went to work and successfully proposed for follow-up director's discretionary time with HST/WFC3, to pin down the source's exact location and measure its properties. Our team obtained these data in late July 2011, and, indeed, a blue star was now clearly visible at the location of the X-ray source. Furthermore, the new source did not correspond exactly with any of the red stars visible in the earlier HST data.

An upper limit from the HST photometry implied that the mass-donating companion must be about 4 M_{Sun} or less. This was an unexpected result because most ULXs are thought to be young objects because their visible counterparts look like short-lived, massive blue stars. In this case, because we have pre-outburst data, we know the blue light arises from the *reprocessing of X-rays* — either on the heated face of the companion star or in portions of the accretion disk around the black hole — and *does not indicate an OB star companion*.

Since pre-outburst data are not available for most ULXs, it raises the question whether a significant number of them may also have low-mass donor stars as well. In any event, with this case, we have proof of the existence of an older population of ULXs, which may be invisible most of the time, and only brighten sporadically.

In another surprise, applying standard accretion models to this object points to a likely black hole mass in excess of 40 M_{Sun} and perhaps as high as 100 M_{Sun} — quite high for a stellar binary system. If the emission was beamed rather than isotropic, a more typical mass estimate like 15 M_{Sun} would be possible, but the time variability characteristics of the source, to the extent that we know them, do not support a beamed model for this source.

While we expect to discover many new surprises as we continue to analyze these fabulous data sets, it will be hard to top the combination of serendipity and excitement generated by this result!

The paper reporting these results appeared in the May 10, 2012, issue of *The Astrophysical Journal*, **750:** 152, with Roberto Soria (Curtin University, Australia) as the first author. Other team members on this study include Knox Long and Brad Whitmore (STScI), Kip Kuntz (Johns Hopkins University), and Paul Plucinsky (Harvard-Smithsonian Center for Astrophysics).

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