Massive Star Birth: A Crossroads of Astrophysics
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Parsec-scale X-ray flows in high-mass star-forming regions

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Abstract. The *Chandra X-ray Observatory* is providing remarkable new views of massive star-forming regions, revealing all stages in the life cycle of high-mass stars and their effects on their surroundings. We present a *Chandra* tour of several high-mass star-forming regions, highlighting physical processes that characterize the life of a cluster of high-mass stars, from deeply-embedded cores too young to have established an HII region to superbubbles so large that they shape our views of galaxies. Along the way we see that X-ray observations reveal hundreds of stellar sources powering great HII region complexes, suffused by both hard and soft diffuse X-ray structures caused by fast O-star winds thermalized in wind-wind collisions or by termination shocks against the surrounding media. Finally, we examine the effects of the deaths of high-mass stars that remained close to their birthplaces, exploding as supernovae within the superbubbles that these clusters created. We present new X-ray results on W51 IRS2E and 30 Doradus and we introduce new data on Trumpler 14 in Carina and the W3 HII region complexes W3 Main and W3(OH).

1. Introduction

Most stars are born in massive star-forming regions (MSFRs); the most massive stars live out their short lives in this environment and eventually transform it when they explode as supernovae. In the meantime, they have a profound influence on their natal neighborhood, generating HII regions and wind-blown bubbles and often triggering new generations of stars to form in the surrounding molecular clouds. The kinetic power of a massive O-star's winds injected into its stellar neighborhood over its lifetime equals that input in its supernova explosion; essentially from the moment they are born high-mass stars cause changes in their environment on parsec scales.

X-ray observations probe different energetic components of MSFRs than traditional optical and IR studies. Stars of virtually all masses and stages emit X-rays in their youth, although the mechanisms for X-ray emission vary with stellar mass. For OB stars excavating an HII region within their nascent molecular cloud, diffuse X-rays may be generated as fast winds shock the surrounding media (Weaver *et al.* 1977); we have recently discovered such diffuse emission with X-ray observations of M 17 and the Rosette Nebula (Townsley *et al.* 2003). X-ray studies also detect the presence of past supernovae through the shocks in their extended remnants.

Chandra and its Advanced CCD Imaging Spectrometer (ACIS) camera give us the sensitivity, spatial resolution, and broad bandpass to detect diffuse X-ray emission generated by these high-mass stars and to separate it from the hundreds of pre-main sequence X-ray-emitting stars seen in these fields. *Chandra* routinely penetrates heavy obscuration ($A_V > 100$ mag) with little source confusion or contamination from unrelated objects to reveal the young stellar populations in MSFRs. Before the *Chandra* era, the relative X-ray contributions of high-mass and low-mass stars, OB winds, and supernova remnant shocks in these regions were largely unknown.

Through the *Chandra* General Observer and Guaranteed Time programs, we are pursuing a multi-year study of MSFRs, cataloguing and characterizing the point source populations (e.g. Getman *et al.* 2005) as well as searching for diffuse emission. Last year we reviewed our *Chandra* observations of M17, RCW49, and W51A (Townsley *et al.* 2004). We show other examples of our program in this contribution, presenting new results for W3, W51A IRS2E, Trumpler 14 in Carina, and 30 Doradus in the LMC.

2. W3

W3 is an obscured complex of high-mass stars, H II regions, and associated molecular clouds situated 2.3 kpc from the Sun, part of a vast star formation complex also containing the W4 superbubble, the massive stellar clusters IC 1805, IC 1795, and NGC 896, and several unnamed IR clusters (Carpenter *et al.* 2000). It is bordered to the west by HB3, a very large, evolved supernova remnant (SNR), which is clearly seen in the *ROSAT* All-Sky Survey image and was observed with *Einstein* (Leahy *et al.* 1985). Radio studies (Routledge *et al.* 1991) suggest that the SNR shock has not yet reached the W3 H II regions, but it is influencing the distribution of CO in the W3 molecular cloud. Lada *et al.* (1978) and Thronson *et al.* (1985) argued that star formation in W3 is being induced by the expansion of W4, which is sweeping up molecular gas into a high-density layer, within which stars are forming. Oey *et al.* (2005) propose that the young (3–5 Myr) OB cluster IC 1795, triggered to form by W4, is blowing its own second-generation superbubble at the molecular cloud interface, triggering in turn the W3 MSFR.

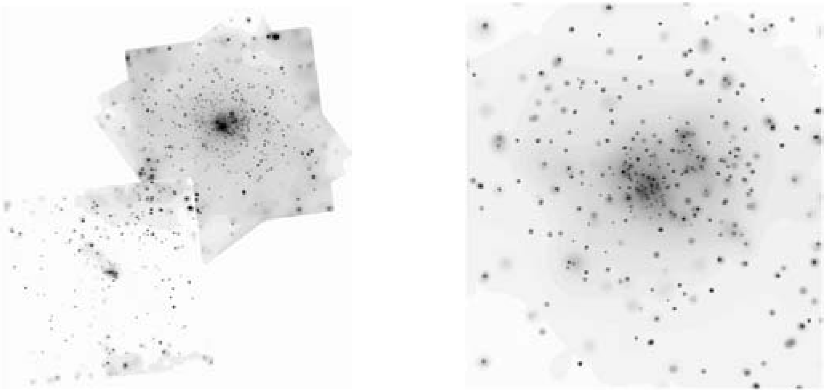

Figure 1. Smoothed hard-band (2–8 keV) images of the W3 MSFR. **Left:** An ACIS-I mosaic of W3, including three pointings on W3 Main totaling 78 ks and a single 72-ks pointing on W3(OH). Each ACIS-I image is $17' \times 17'$, or ∼11 pc on a side. **Right:** A zoomed image of W3 Main, showing the large number of young, embedded stars revealed by this observation.

A 40-ksec *Chandra* observation of W3 Main using the ACIS imaging array (ACIS-I) revealed the ionizing sources for many of its HII regions and over 200 point sources (Hofner *et al.* 2002). We have recently obtained more *Chandra*/ACIS-I observations of W3 Main and the adjacent field W3(OH) (Figure 1), showing a rich stellar population around W3 Main, the older cluster IC 1795 (perhaps exhibiting soft diffuse emission), and several small embedded clusters in and around W3(OH). The W3(OH) field is noticeably lacking in sources compared to the W3 Main field. Although partly an obscuration effect, this also illustrates the intrinsic difference in the size of these clusters; hard X-rays are largely unaffected by the obscuring material so the 2–8 keV mosaic image in Figure 1 reflects an intrinsic difference in cluster size between W3(OH) and W3 Main.

3. W51A and the Enigmatic Source IRS2E

W51 is one of the most massive star-forming complexes in the Galaxy but is difficult to observe because of its distance (∼7 kpc) and high obscuration. Our 72-ksec *Chandra*/ACIS observation of W51A (Townsley *et al.* 2004) detected many of the known radio HII regions (Mehringer 1994) as diffuse X-ray sources. We also see ∼450 point sources, revealing the highest-mass and youngest inhabitants fueling the HII regions and just emerging from their dusty natal cocoons.

Buried in one of the youngest and richest high-mass complexes, G49.5-0.4, we have discovered an enigmatic hard X-ray source at the center of an embedded high-mass stellar cluster (Figure 2). CXOW51 J192340.1+143105 is spatially coincident with a deeply-embedded mid-IR source (Kraemer *et al.* 2001) known as IRS2 East (IRS2E). It is surrounded by powerful masers and ultra-compact HII regions yet has no associated radio HII region itself. Evidence for infall is seen in this region (Sollins *et al.* 2004).

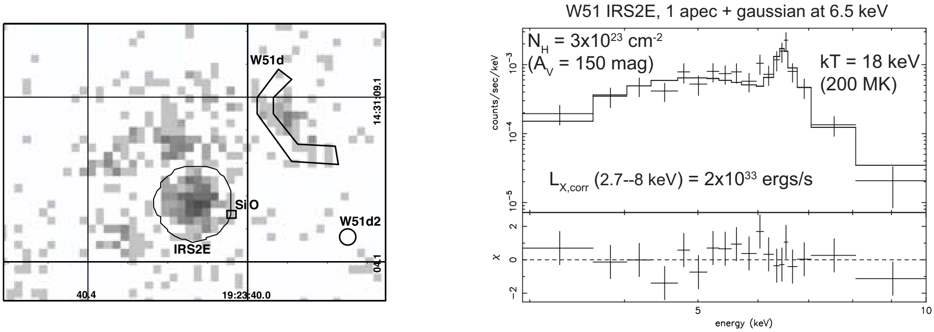

Figure 2. Left: A binned ACIS image of the W51 IRS2 complex, $8'' \times 12''$, with a J2000 coordinate grid. The extraction region for IRS2E, containing 90% of the 1.5 keV point spread function, is shown, as is the cometary HII region W51d. The locations of the UCHII region W51d2 and the strong SiO maser are noted. **Right:** ACIS spectrum of W51 IRS2E: the upper panel shows the source spectrum and model fit; the lower panel shows the fit residuals.

IRS2E emits most of its X-ray photons in a broad 6.5-keV line probably due to fluorescent iron. Although common in AGN, this type of X-ray spectrum is highly unusual for stellar sources, as it requires an embedded source with substantial emission above the iron absorption edge (7.1 keV). Such a hard X-ray spectrum could be generated by colliding winds in a massive cluster (Cantó *et al.* 2000), but the X-ray emission of IRS2E varies by a factor of two in 40 ksec, ruling out the cluster explanation. We suspect that it is a colliding wind binary, perhaps a younger version of Eta Carinae (Corcoran *et al.* 2004) or HD 5980, a luminous blue variable in the SMC (Nazé *et al.* 2002). The absence of an HII region around this source suggests that it is very young.

4. Trumpler 14 in Carina

The Carina complex, at a distance of ∼2.8 kpc (Tapia *et al.* 2003), is a remarkably rich star-forming region at the edge of a giant molecular cloud (GMC), containing 8 open clusters with at least 64 O stars, 2 Wolf-Rayet stars, and the luminous blue variable Eta Carinae (Feinstein 1995). *ISO* discovery of 22μm grains in the bright radio HII region Carina I may imply that a supernova occurred in this region (Chan & Onaka 2000); the presence of WR stars also may indicate past supernovae, although no well-defined remnant has ever been seen.

Tr 14 is an extremely rich, young (∼1 My), compact OB cluster near the center of the Carina complex, containing at least 30 O and early B stars (Vázquez *et al.* 1996). Tr 14 is probably at the same distance as its neighboring, equally rich cluster Trumpler 16 but is thought to be younger (Walborn 1995). These two clusters contain the highest concentration of O3 stars known in the Galaxy; their ionizing flux and winds may be fueling a bipolar superbubble (Smith *et al.* 2000).

An *Einstein* X-ray study of the Carina star-forming complex was performed by Seward & Chlebowski (1982). They detected $\sim$30 point sources, mostly individual high-mass stars and the collective emission from unresolved cluster cores. They also detected diffuse emission pervading the entire region and speculated that it may be due to O star winds. Based on experience with *Chandra*, we now know that thousands of the lower-mass stars in these young clusters were likely to be contributing to the diffuse flux seen in the *Einstein* data. A major goal of our *Chandra* observation was to resolve out a significant fraction of this point source emission so a better determination of the spatial and spectral characteristics of the diffuse component can be made.

Figure 3. Left: A smoothed, soft-band (0.5–2 keV) image of the 57-ksec ACIS observation of Tr 14 in Carina, with the cluster imaged on the ACIS-I array ($17' \times 17'$, or $\sim$14 pc on a side at D = 2.8 kpc) and bright diffuse emission seen in the off-axis S2 and S3 CCDs (each $8.5' \times 8.5'$). We find $\sim$1600 point sources on the I array plus extensive diffuse emission across the whole field. **Right:** Smoothed full-band (0.5–8 keV) image of the 21-ksec ACIS observation of 30 Doradus, with 30 Dor Main imaged on the I array (covering $\sim$250 pc on a side at D = 50 kpc); the large shell 30 Dor C, the Honeycomb SNR, and SN1987A are seen in the off-axis CCDs S3 and S4. Bright, soft diffuse emission dominates the field.

The aimpoint of our 57-ksec ACIS observation of Tr 14 (Figure 3 left) was the central star in the cluster, HD 93129AB, a very early-type (O2I–O3.5V) binary (Walborn *et al.* 2002), with the two components separated by $\sim 1''$. Since these are resolved in the ACIS data, we can see that the two components have very different spectra; HD 93129B shows a typical O-star X-ray spectrum ($kT = 0.5$ keV, or $T \sim 6$ MK), while HD 93129A shows a similar soft component ($kT = 0.6$ keV) but also exhibits a much harder component, with $kT = 3.0$ keV ($T \sim 35$ MK), and is ten times brighter in X-rays than HD 93129B. This hard spectrum and high X-ray luminosity are indicative of a colliding-wind binary (Portegies Zwart *et al.* 2002); in fact HD 93129A was recently discovered to be a spectroscopic binary (Nelan *et al.* 2004). Additionally, while the O3V star HD 93128 is soft and fainter in X-rays, we find that the O3V star HD 93250 in Tr 14 shows a two-component spectrum and X-ray luminosity almost identical to HD 93129A. *XMM-Newton* observations also show a hard spectral component for HD 93250 (Albacete Colombo *et al.* 2003); this source is very likely a colliding-wind binary as well.

The diffuse emission in Tr 14 is quite soft and shows abundances typical of OB wind termination shocks. We also see soft, bright diffuse emission in the off-axis CCDs of the ACIS array, far from any of the Carina massive stellar clusters. Spectral fits to this diffuse emission require abundances of O, Ne, Si, and Fe to be more than twice the solar value; this is evidence that the emission may be from an old "cavity" supernova remnant that exploded inside the Carina superbubble, as suggested by Chu *et al.* (1993).

5. 30 Doradus

Early in the *Chandra* mission, we obtained a ∼21 ksec observation of the most luminous Giant Extragalactic HII Region and "starburst cluster" in the Local Group, 30 Doradus in the Large Magellanic Cloud. The ACIS pointing was centered on the young, dense OB cluster R136, a testbed for understanding recent and ongoing star formation in the 30 Dor complex. The presence of evolved supergiants ∼25 Myr old and embedded massive protostars shows that 30 Dor is the product of multiple epochs of star formation, including a new generation of embedded stars currently forming, possibly as a result of triggered collapse from the effects of R136 (Brandner *et al.* 2001). Supernovae pervade the region but may go undetected due to age and environment (Chu & Mac Low 1990). Nearby are two msec pulsars and SN1987A. 30 Dor produced at least five plasma-filled superbubbles with ∼100-pc scales (Wang & Helfand 1991), likely products of strong OB winds and multiple supernovae.

The right panel of Figure 3 shows a smoothed ACIS image from our 21-ksec observation of 30 Dor, including the off-axis CCDs S3 and S4 as well as the main 30 Dor nebula on the ACIS-I array. We see a bright concentration of X-rays associated with the R136 star cluster, the bright SNR N157B to the southwest, a number of new widely-distributed compact X-ray sources, and diffuse structures associated with the superbubbles produced by the collective effects of massive stellar winds and their past supernova events (Townsley *et al.* 2005a). Some of these are center-filled while others are edge-brightened, indicating a complicated mix of viewing angles and perhaps filling factors.

Our spectral analysis of the superbubbles reveals a range of absorptions ($N_H = 1$–6×10^{21} cm^{-2}), plasma temperatures ($T = 3$–9×10^{6} K), and abundance variations. We find ∼100 sources associated with the central massive cluster R136 (Townsley *et al.* 2005b); some bright, hard X-ray point sources in the field are likely colliding-wind binaries (Portegies Zwart *et al.* 2002). Comparing the X-ray data to visual and IR images, we find that hot plasma fills the shells outlined by ionized gas and warm dust.

6. Summary

Interactions between powerful O star winds and the ISM lead to parsec-scale soft X-ray emission as predicted by Weaver *et al.* (1977) and others, but with much fainter X-ray luminosities; this hot plasma may pervade the Galactic plane but is hard to detect due to obscuration. Wind-wind interactions lead to harder X-rays; this emission may provide a way to determine close binarity in massive stars or to detect embedded massive clusters. The 10^4K Strömgren Sphere that defines classical HII regions is really a Strömgren Shell filled with 10^6K plasma in many MSFRs. Only a small portion of the wind energy and mass appears in the observed diffuse X-ray plasma, though; it could be dissipated via turbulence, mass-loading, or fissures into the ISM (Townsley *et al.* 2003). We see bright, soft diffuse X-rays in some regions; enhanced metallicity and luminosity compared to wind-generated emission and the presence of these structures in regions that also contain evolved stars implies that these X-ray features are the remains of cavity SNRs.

Chandra chronicles the life cycle of massive stars through studies of MSFRs. In W3 and W51A we see massive embedded protostars; winds from main sequence O stars fill M17 and Tr14 with soft X-rays. Colliding-wind binaries appear as hard X-ray sources in Tr14, W51 IRS2E, and 30 Dor. Cavity supernova remnants dominate the soft diffuse X-ray emission in Carina and 30 Dor, enhancing the superbubbles blown by the winds of massive stars.

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