The Tarantula – Revealed by X-rays (T-ReX)

A Definitive Chandra Investigation of 30 Doradus

Our first impressions of spiral and irregular galaxies are defined by massive star-forming regions (MSFRs), signposts marking spiral arms, bars, and starbursts. They remind us that galaxies really are evolving, churned by the continuous injection of energy and processed material. MSFRs offer us a microcosm of starburst astrophysics, where winds from O and Wolf-Rayet (WR) stars combine with supernovae to carve up the neutral medium from which they formed, both triggering and suppressing new generations of stars. With X-ray observations we see the stars themselves—the engines that shape the larger view of a galaxy—along with the hot, shocked ISM created by massive star feedback, which in turn fills the superbubbles that define starburst clusters (Fig. 1).

We propose the 2 Ms *Chandra*/ACIS-I X-ray Visionary Project **T-ReX**, an intensive study of 30 Doradus (The Tarantula Nebula) in the LMC, the most powerful MSFR in the Local Group. To date *Chandra* has invested just 114 ks in this iconic target—proportionally far less than other premier observatories (e.g. *HST*, VLT, *Spitzer*, VISTA)—revealing only the most massive stars and large-scale diffuse structures. This very deep observation is essential to engage the great power of *Chandra*'s unparalleled spatial resolution, a unique resource that will remain unmatched for another decade. **T-ReX** will reveal the X-ray properties of hundreds of 30 Dor's low-metallicity massive stars [1], thousands of lower-mass pre-main sequence (pre-MS) stars that record its star formation history [2], and parsec-scale shocks from winds and supernovae that are shredding its ISM [3,4]. With *Chandra*, 30 Doradus becomes our microscope on the high-energy astrophysics of starbursts.

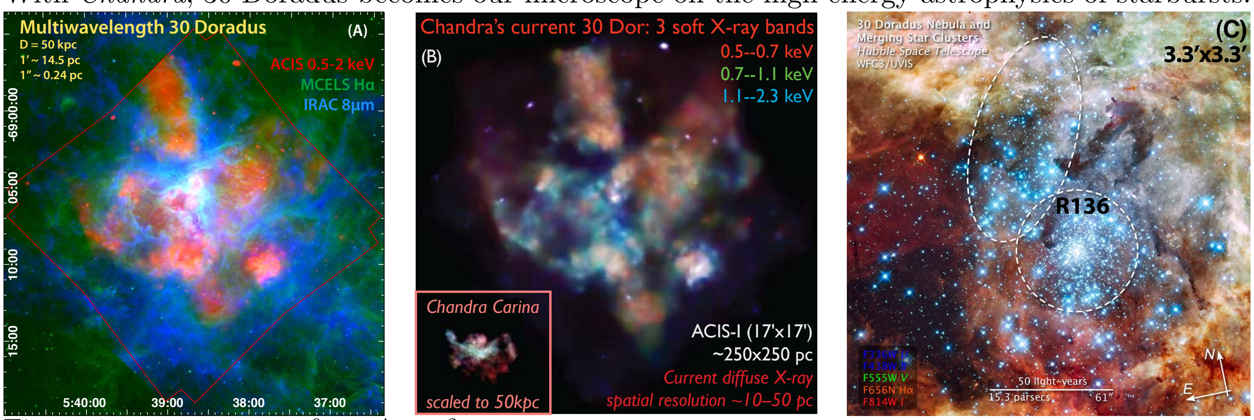

Figure 1: **(A)** 30 Dor at 10^6K, 10^4K, 10^2K. Hot plasma (X-ray) threads 50-pc-sized superbubbles outlined by dense ionized gas (Hα), in turn surrounded by PAH and heated dust continuum emission (8μm). **(B)** Diffuse soft X-ray emission in 30 Dor and the Carina Nebula (inset: 22-pointing ACIS-I Carina mosaic [5] scaled to the LMC distance). 30 Dor's hot ISM is likely as spatially complex as Carina's, but is so far unresolved. **(C)** 30 Dor central. *HST*/WFC3 view of 30 Dor's 1–2 Myr-old main cluster R136 and a 2–5 Myr-old population that may be merging with it [6].

This definitive *Chandra* characterization of 30 Dor is motivated by the fundamental need to understand the complex machinery of a starburst: its massive stars, their remnants, the lower-mass populations that accompany them, and the profound influence they exert on dense molecular clouds, through radiation and mechanical feedback, that both perpetuate and quench star formation. 30 Dor is the Olympus Mons of MSFRs: with no differential galactic rotation to rip the complex apart, it persists and grows at the confluence of two supergiant shells that have provided it with the fuel to power massive star formation for at least 25 Myr, reaching starburst proportions. Today it is dominated by its 1–2 Myr-old central massive cluster R136, containing the richest young stellar population in the Local Group, including the most massive stars known. 30 Dor's LMC location offers us a nearly face-on, low-metallicity starburst laboratory with low intervening absorption and a well-known distance, in contrast to Galactic MSFRs. **T-ReX** will show how hot plasmas relate to the complex cold ISM structures, ionization fronts, and photon-dominated regions seen in the visual and IR. With its unparalleled sample of the most massive, low-metallicity stars available to us, **T-ReX** will provide insights into the ionizing sources from an earlier cosmic time.

T-ReX Science Goals

T-ReX will illuminate many astrophysical mysteries regarding the formation and evolution of the most massive stars, MSFRs, and starbursts. These galactic building blocks all emit X-rays, but they blur together in distant starburst galaxies. With 30 Dor we can quantify the relative contributions of the diverse sources that constitute the X-ray emission of a starburst: the stars themselves (single very massive stars, magnetic OB stars, colliding-wind binaries, intermediate-mass pre-MS stars (IMPS), low-mass pre-MS stars), stellar remnants (pulsars, X-ray binaries), and diffuse shock emission (from OB winds, individual young supernova remnants (SNRs), thermalized cavity SNRs, superbubbles). **T-ReX** will map the variations in X-ray plasma temperature, density, pressure, and metallicity across 30 Dor, quantifying their effects on its dynamics and evolution.

This is our best opportunity to dissect a starburst and the potential for discovery is multifaceted; **T-ReX** will advance a host of bedrock high-energy astrophysics themes (e.g. massive stars and their feedback, young stellar populations, the hot ISM, SNRs, evolved objects, starbursts). Below we demonstrate the scope of **T-ReX** science goals by listing 27 planned team papers (with lead authors) that directly use **T-ReX** data. Some of these assume **T-ReX** results, but most are solidly based on extrapolations of available *Chandra* data on 30 Dor and other MSFRs; many stem from our experience developing the *Chandra* Carina Complex Project (CCCP; a 1.2 Ms *Chandra* AO9 Very Large Project) [5]. Multiwavelength efforts and **T-ReX** surprises will augment these studies.

- "The Tarantula–Revealed by X-rays (T-ReX): An Intensive *Chandra* Study of 30 Dor," Townsley
- "The T-ReX Catalog of X-ray Point Sources and Membership Probabilities in 30 Dor," Broos
- "X-ray Properties of the 25 Wolf-Rayet Stars in 30 Dor," Crowther
- "The $L_X/L_{\rm bol}$ Relation at Low Metallicity: Massive Stars in 30 Dor," Gagné
- "Metallicity Effects on the Line-Driven Instability of Massive Star Winds," Sundqvist
- "Clumping-Independent X-ray Mass-Loss Determination of Massive Stars in 30 Dor," Cohen
- "Orbital Modulation of X-ray Emission from Colliding-Wind Binaries in 30 Dor," Sana
- "Candidate Magnetic Massive Stars in 30 Dor," Petit
- "Relating X-ray Emission Mechanisms to OB Star Optical/UV Parameters in 30 Dor," Walborn
- "The Origin of X-ray Emission from B-type Main Sequence Stars in 30 Dor," Petit
- "Properties of X-ray-bright Intermediate-Mass Pre-MS Stars (IMPS) in 30 Dor," Povich
- "Spatial Structure of Pre-MS Stellar Populations in 30 Dor from T-ReX," Feigelson
- "Pre-MS Star X-ray Superflares and the Ionization of Protoplanetary Disks," Getman
- "Enhancing IMF Studies of 30 Dor Pre-MS Populations with X-ray-Selected Samples," Gouliermis
- "Feedback and Young Stars from T-ReX: Implications for Star Cluster Formation Theory," Tan
- "T-ReX Maps of Diffuse X-ray Emission and Inferred Plasma Properties in 30 Dor," Townsley
- "A Multiwavelength Search for X-ray Plasma Escape Routes in 30 Dor," Pellegrini
- "X-ray Plasma Properties of 30 Dor Regions with High Hα Expansion Velocities," Torres Flores
- "Interpreting 30 Dor's Diffuse X-ray Emission via Massive Star Feedback Simulations," Pittard
- "30 Doradus: Chemical Enrichment from Massive Stars in a Closed Box," Wang
- "A Detailed Study of PSR J0537-6910 and the SNR N157B from T-ReX," Slane
- "A Search for the Remains of Supernova Remnants in 30 Dor with T-ReX," Slane
- "Non-thermal Diffuse X-ray Emission in 30 Dor," Lopez
- "High-mass X-ray Binaries in 30 Dor Discovered by T-ReX," Clark
- "T-ReX Insights into the Star Formation History of 30 Dor," Sana
- "30 Dor and T-ReX: The X-ray Anatomy of a Starburst," Wang
- "Using 30 Dor to Interpret X-Ray Observations of Extragalactic Super Star Clusters," Johnson

30 Doradus: A Field of Superlatives

30 Dor offers us the most extreme example of star formation resolvable by the world's premier telescopes; it is the most massive and luminous MSFR in the Local Group, containing several thousand massive stars and IMPS, plus several hundred thousand lower-mass pre-MS stars. Its central young cluster R136 has 1000× the ionizing radiation of Orion [7] and at least 5× as many early-O stars as Carina [8]. It contains several of the most massive stars known [1] and the full complement of massive binaries, including WR-WR, WR-O, and O-O systems [9]. In the wider 30 Dor field, the presence of ∼25 Myr-old evolved supergiants and embedded massive young stellar objects shows that 30 Dor is the product of multiple epochs of star formation [2]; the newest generation of embedded stars may represent triggered collapse from the effects of R136 [10].

Our understanding of 30 Dor is evolving in real time, due to large recent investments by state-of-the-art global and space-based facilities. For example, the VLT Flames Tarantula Survey (VFTS) [8] provides optical spectroscopy (radial velocities, spectral types) for >800 massive stars in a $20' \times 20'$ field around 30 Dor. VISTA [11] gives Y, J, and multi-epoch Ks photometry reaching J=22. OGLE provides V- and I-band lightcurves to check for variability [12]. Recent *HST*/WFC3 programs [6,13] use visual and near-IR photometry to identify >1000 pre-MS stars in the central few arcminutes around R136; new *HST* programs are ongoing to obtain wide-field photometry, proper motions of massive stars, and spectroscopy of the most massive systems in R136 [PI's Sabbi, Lennon, and Crowther, respectively]. *Spitzer*'s "Surveying the Agents of a Galaxy's Evolution" [14] gives mid-IR photometry especially helpful for characterizing IMPS. The first ALMA results [15] and new ISM kinematics studies [16] are emerging.

Current shallow *Chandra* observations reach just the top of the X-ray luminosity function, detecting a few WR and early-O stars (Fig. 2) [17,18] and only 28 VFTS sources; many of these exhibit hard X-ray emission consistent with colliding-wind binaries and/or magnetic massive stars [19]. **T-ReX** will perform a comprehensive study of ∼400 reduced-metallicity massive stars, including >50 early-O stars (O2–O5; CCCP had 8), most WR stars (outside the R136 core), ∼30 magnetic O stars, and >100 O+OB binaries [20], all with excellent X-ray spectra and lightcurves, allowing for time-resolved X-ray spectroscopy and estimates of the massive star $L_X/L_{\rm bol}$ relation [21] and mass-loss rates [22] for starburst environments at cosmological distances. We expect orbital X-ray modulation in many massive binaries, as we have found in Galactic MSFRs. A third of these will be short-period (<25d) systems; for these, **T-ReX** will sample several orbital cycles as 50–100 ks observations are performed randomly throughout the year to build up the full **T-ReX** exposure.

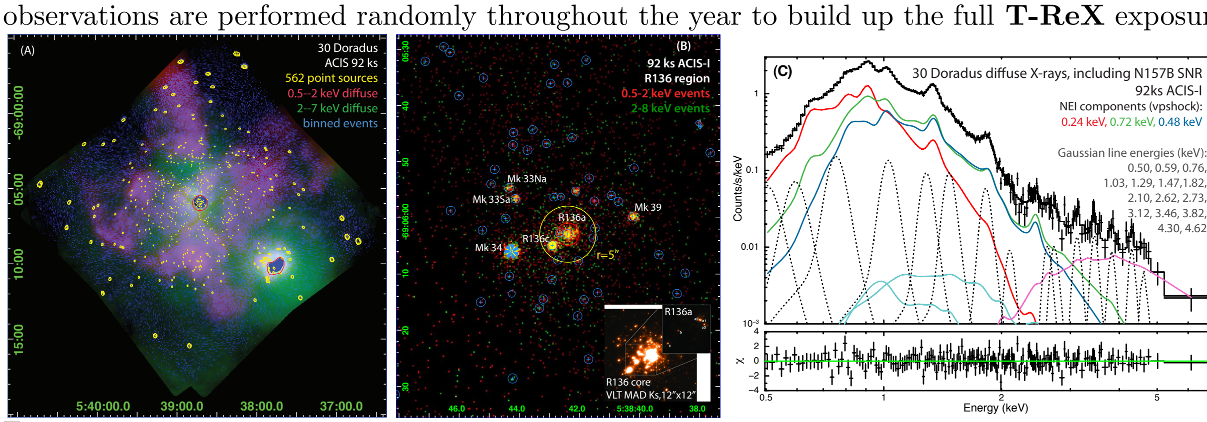

Figure 2: **(A)** The AO6 *Chandra* observation of 30 Dor, full-field ACIS-I [18] (due to calibration differences, the 22-ks AO1 data were analyzed separately [17,23]). **(B)** ACIS field center on R136 with some bright WR stars labeled (inset at lower right shows VLT adaptive-optics data [1]). The central red circle (radius $2''$) contains the cluster core; **T-ReX** will be confusion-limited out to $5''$ (yellow circle) (see Fig. 4A). **(C)** Global diffuse X-ray spectrum for 30 Dor [18], fit using *vpshock* and *apec* model components as for CCCP, with gaussians added (dotted lines) to fit spectral lines not well-modeled by the thermal plasmas. Soft gaussians may indicate charge exchange processes at work [24,25]; hard gaussians are necessary for the N157B SNR.

The vast intermediate- and low-mass pre-MS populations of 30 Dor remain mostly undiscovered in the current shallow *Chandra* data [18]. **T-ReX** will provide the largest X-ray sample of IMPS ($\sim$2–8 $M_\odot$ pre-MS stars) available; while main sequence intermediate-mass stars are X-ray-faint, IMPS show enhanced X-ray emission probably because they are still contracting and convective [26]. This new area of study can meld *Chandra*, *HST*, and *Spitzer* data with great discovery potential.

While visual and IR studies can access parts of 30 Dor's clustered low-mass pre-MS populations (e.g. [6,13]), they face large contaminating populations and bright nebular emission; X-ray studies alone provide the critical complementary sample of individually identified older pre-MS stars with cleared inner disks that is necessary for an accurate low-mass population census and clustering analysis, as many Galactic MSFR studies have shown [27]. **T-ReX** will also pinpoint 30 Dor's large "distributed" pre-MS population; these unclustered young stars made up half of Carina's pre-MS population [28] and reveal how a "cluster-of-clusters" complex dissolves over several Myr. Because of its long duration and 30 Dor's large pre-MS populations, **T-ReX** will sample hundreds of pre-MS "superflares," with peak $L_X > 10^{31}$erg/s [29]; these flares can irradiate and ionize protoplanetary disks, reducing dead zones and affecting dust settling and other planet formation processes. **T-ReX** provides a better opportunity to characterize superflares than any X-ray study to date.

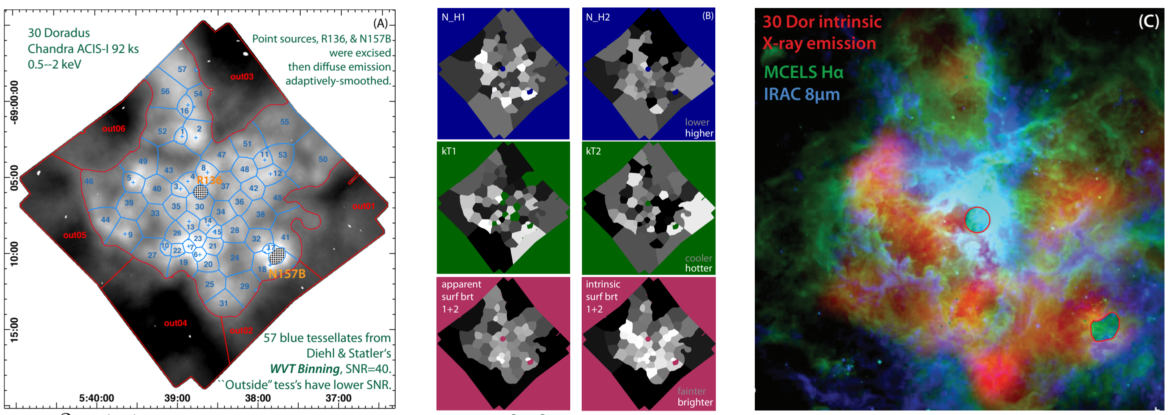

Figure 3: **(A)** 30 Dor's diffuse X-ray emission [18]. Areas of high apparent surface brightness were tessellated into $\sim$10–50 pc regions with comparable signal-to-noise. The confused R136 core and non-thermal parts of N157B were excluded. **(B)** Spectral fits with multi-temperature thermal plasma models were performed on each tessellate to estimate plasma properties. Here intrinsic surface brightness is inferred from apparent surface brightness by using plasma temperatures and absorbing columns from the spectral fits. **(C)** Same as Fig. 1A, but now with inferred *intrinsic* surface brightness (absorption effects removed). **T-ReX** will provide these X-ray maps at 1–10 pc resolution.

The $\sim$2.5-Myr-old MSFR NGC 2060 lies $\sim 6'$ southwest of R136 (Fig. 3A). In X-rays, NGC 2060 is dominated by the young SNR N157B [23] containing the 16-ms PSR J0537-6910, the most energetic pulsar known, and its prominent cometary pulsar wind nebula [30], a TeV gamma ray source (probably due to inverse-Compton scattering of the surrounding bright IR radiation field [31]). SNRs must pervade 30 Dor but are difficult to detect individually due to age and environment [32].

30 Dor exhibits at least five plasma-filled superbubbles with $\sim$100-pc scales [3], products of strong OB winds and multiple supernovae. Because of their proximity and the low absorbing column to the LMC, they provide the best opportunity to study the X-ray spectrum and structure of any superbubble system; this is especially important since superbubbles are thought to be major cosmic ray factories [33]. *Chandra* has already shown [18,23,25,34,35] that they are spatially complex X-ray structures with a range of X-ray plasma temperatures, ionization timescales, absorptions, and luminosities (Figs. 1B, 2C, 3). As in Carina and other MSFRs, 30 Dor's ISM appears to be a complex labyrinth of low-density cells and channels filled with hot plasma, surrounded by walls of colder material; the energetics of mechanical feedback must be placed in this context of catacombs (Fig. 4C) if we are to understand HII region physics and the evolution of the hot ISM. *Chandra*'s spatial resolution and the deep observation of **T-ReX** (to populate the 30 Dor field with diffuse X-ray photons) are paramount for this task; no amount of blurry data will accomplish this science.

Chandra Feasibility and Predicted Results

30 Dor has an extreme ecliptic latitude (−87°), limiting **T-ReX** to 2 Ms due to CXC rules motivated by spacecraft thermal constraints. Here we detail the 30 Dor populations accessible with this integration time and demonstrate that this *Chandra* observation will yield the data needed to realize the science potential of **T-ReX** described above. From PRoVis, 30 Dor always violates the pitch angle constraint but with high visibility per orbit (≥0.75). Thus 30 Dor is always accessible to *Chandra* but observations must be short (∼50–100 ks) and sparsely scheduled to manage thermal loading. Thus we can expect 20–40 new ObsIDs for **T-ReX**, with random roll angles and random time sampling throughout the year. We will combine these with the existing ACIS-I data (5 ObsIDs from AO1 and AO6) to give a 15-year baseline for bright source lightcurves [36], then do custom source searching [17] on the merged data to achieve the deepest possible sensitivity, especially in crowded regions. The resulting sub-arcsecond source positions will enable the multiwavelength studies critical for determining source properties.

Using PIMMS, the table below presents 2 Ms, Cycle 15 ACIS-I sensitivity limits for single O stars, colliding-wind binaries or magnetic massive stars, and pre-MS stars in 30 Dor (assuming *apec* thermal plasmas, D=50 kpc, an R136 aimpoint, and two typical absorbing columns [13]), plus the expected number of detected AGN [37] (assuming a power law spectrum and the worst-case lower column). **T-ReX** will produce excellent spectra and detailed lightcurves for the >500 objects detected so far plus many others, even though sensitivity to faint sources right in the dense core of R136 (<5″ off-axis) will be limited by crowding (Figs. 2B and 4A). In the central ∼3′ (i.e. the entire region around R136 shown in Fig. 1C), the faintest detectable sources reach the limits in Row 1. **T-ReX** 6-count completeness limits [38] there (Row 2) are sufficient to detect nearly all massive stars earlier than O8 [39]. Farther off-axis (Row 3), the 16-count completeness limit [38] is sufficient to detect the brighter half of the O star population [39] consistently across the full field; many more sources will be detected reliably with half that many counts.

	off-axis angle (arcmin)	limit (type) (net events)	**single O** (kT=0.4keV)	**CWB/magnetic O** (kT=1.9keV)	**pre-MS** (kT=2.7keV)	**AGN** (Γ=1)
			Limiting unabsorbed log L_X for A_V = 0.5 (1.5) mag (erg s^{-1}, 0.5–8 keV, Z=0.4Z$_\odot$)			A_V = 0.5 (# detected)
1.	0.1 − 3	3 (faintest)	30.7 (30.9)	30.6 (30.7)	30.7 (30.8)	· · ·
2.	0.1 − 3	6 (complete)	31.0 (31.2)	30.9 (31.0)	31.0 (31.1)	105
3.	3 − 8	16 (complete)	31.4 (31.6)	31.4 (31.5)	31.4 (31.5)	300

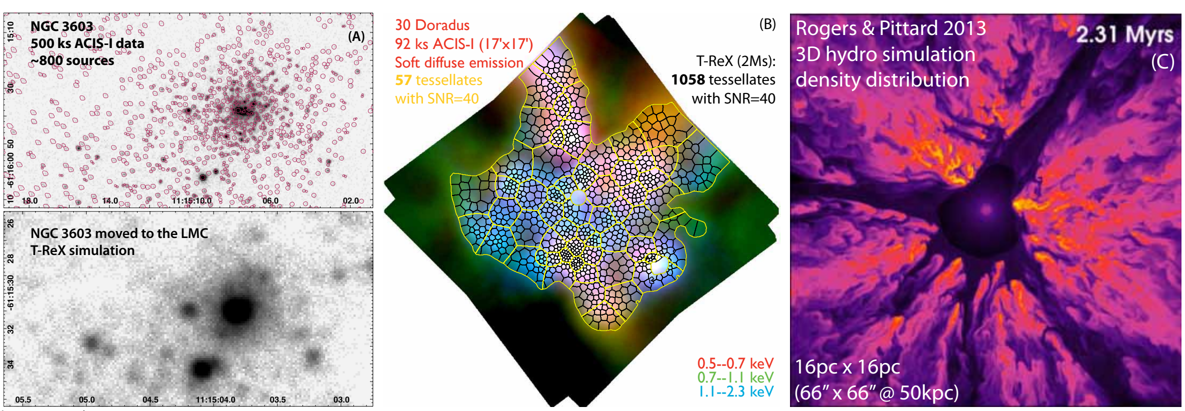

Figure 4: **T-ReX** simulations. **(A)** Predicting the R136 scene using the Galactic MSFR NGC 3603 as a proxy (zoom for detail). Top shows NGC 3603 ACIS data; bottom simulates the same scene (in pc) in 2 Ms at 50 kpc (including instrumental background) with the X-ray luminosity function scaled to match R136. Just the central ∼5″ is confused. **(B)** Mapping the hot ISM. Current data support 57 diffuse tessellates with signal-to-noise adequate for spectral fitting (see Fig. 3A). **T-ReX** would provide 1058 such tessellates (shown here in black); of course the underlying image would show much more structure. **(C)** The simulated ISM density structure surrounding a modest MSFR, with channels carved by the winds of just 3 O stars [40]. The channels (black) are filled with 10^7K gas [41].

T-ReX will characterize hundreds of IMPS, for a detailed exploration of this X-ray-bright but only recently studied population [26]. Although only $\sim$1% of low-mass pre-MS stars ($<$2 $M_\odot$) exceeds $\log L_X = 31.2$ [42], **T-ReX** should detect several thousand pre-MS stars across the field assuming a typical stellar initial mass function, as 30 Dor is thought to contain several $\times 10^5$ young stars [7]. For $\sim 3'$ around R136, we will capture $\sim$10% of the pre-MS population and reach the brightest examples down to 0.4 $M_\odot$, seeing 20–50% of sources above 0.5 $M_\odot$ (several thousand more stars). Once all these point sources are detected and removed, **T-ReX** will produce *over a thousand diffuse tessellates* (Fig. 4B)—18× the current number—with enough counts for detailed spectral analysis and 1–10 pc spatial resolution of the hot gas; state-of-the-art simulations of massive star feedback (Fig. 4C) show that such fine detail is necessary to start to understand MSFR energetics.

Note that all limiting luminosities would be increased by 0.3 in the log if **T-ReX** were decreased from 2 Ms to 1 Ms. Most pre-MS star science (clustering, population studies, 30 Dor star formation history) and studies of late-O/early-B stars would be lost. Fewer variable sources would be captured; orbital modulation studies would be limited to systems with shorter periods. Statistical studies of O star X-ray emission would be limited to the central $3'$ of the ACIS-I field. Spatial resolution of diffuse structures would be reduced substantially, with just half as many diffuse tessellates.

Project Management and Data Distribution Plan

The large team of **T-ReX** investigators is made up of project leaders from multiwavelength ground- and space-based studies of 30 Dor and other major *Chandra* studies of MSFRs and SNRs. Project organization will be patterned after the CCCP (PI Townsley) [5]. Data analysis will be performed by Townsley, with custom tools developed as needed by software engineer Patrick Broos; science analysis and publication will start with Townsley and Broos but will then be distributed across the team to take full advantage of the breadth of expertise available. Multiwavelength projects that fold the new *Chandra* results into the many ongoing ground- and space-based studies of 30 Dor will be led by the **T-ReX** co-investigators that are specialists in those studies.

We will publish a complete set of X-ray properties for all **T-ReX** point sources [38], spectral fits for sources with sufficient counts [43], and spectral fits and model parameter maps (Fig. 3B) for all diffuse tessellates [18,24]. We will make available on the web our single- and multi-ObsID event lists, images, and exposure maps, and a standardized set of data products [44] for every point source and diffuse tessellate; an example is available for the famous "slow runaway" WR star VFTS 682 [45] in the current 30 Dor ACIS data [46]. Anyone will be able to fit their own spectral models by downloading (via *wget*) single-ObsID or multi-ObsID extracted spectra, custom background spectra, and calibration files for any and all sources/tessellates of interest.

Data analysis for this project will be difficult and time-consuming, requiring individual treatment of $\gtrsim$40 ObsIDs and resulting in X-ray properties for $\sim$400 massive stars, $\sim$3000–6000 other point sources, and $>$1000 diffuse tessellates; we anticipate substantial required code development to further automate our diffuse analysis procedures and to augment science analysis tools such as time-resolved spectroscopy. As resources permit, we will continue to improve our specialized ACIS analysis software [36,47] and release it to the community, as we have done throughout the mission.

1. Crowther et al. 2010, MNRAS 408, 731
2. Walborn & Blades 1997, ApJS 112, 457
3. Wang & Helfand 1991, ApJ 370, 541
4. Chu & Kennicutt 1994, ApJ 425, 720
5. *Chandra* Carina Complex Project (CCCP): 2011 ApJS *Special Issue*, Vol. 194, 16 papers
6. Sabbi et al. 2012, ApJ 754, L37
7. Conti, Crowther, & Leitherer 2008, "From Luminous Hot Stars to Starburst Galaxies"
8. Evans et al. 2011, A&A 530, #108
9. Crowther & Dessart 1998, MNRAS 296, 622
10. Walborn et al. 2013, AJ 145, #98
11. Cioni et al. 2011, A&A 527, #116
12. Udalski 2003, AcA, 53, 291
13. De Marchi 2011, ApJ 739, #27
14. Meixner et al. 2006, AJ 132, 2268
15. Indebetouw et al. 2013, in prep
16. Torres-Flores et al. 2013, A&A submitted
17. Townsley et al. 2006, AJ 131, 2164
18. Townsley, Broos, et al. 2013, AJ in prep
19. Petit et al. 2013, MNRAS 429, 398
20. Sana et al. 2013, ASPC 465, 284
21. Berghofer et al. 1997, A&A 322, 167
22. Cohen et al. 2011 MNRAS 415, 3354
23. Townsley et al. 2006, AJ 131, 2140
24. Townsley et al. 2011, CCCP #15
25. Townsley et al. 2011, CCCP #16
26. Povich et al. 2011, CCCP #14
27. Feigelson et al. 2013, ApJS submitted
28. Feigelson et al. 2011, CCCP #9
29. Getman et al. 2008, ApJ, 688, 418
30. Chen et al. 2006, ApJ 651, 237
31. H.E.S.S. collaboration 2012, A&A 545, L2
32. Chu & Mac Low 1990, ApJ 365, 510
33. Lingenfelter 2012, AIP (arXiv:1209.5728)
34. Lopez et al. 2011, ApJ 731, #91
35. Pellegrini et al. 2011, ApJ 738, #34
36. Broos et al. 2010, ApJ 714, 1582
37. Lehmer et al. 2012, ApJ 752, #46
38. Broos et al. 2011, CCCP #2
39. Nazé et al. 2011, CCCP #7
40. Rogers & Pittard 2013, MNRAS 880
41. Rogers & Pittard 2013, in prep
42. Preibisch et al. 2005, ApJS 160, 401
43. Gagné et al. 2011, CCCP #5
44. http://www2.astro.psu.edu/xray/docs/TARA/ae_users_guide/standardized_directory_tree.html
45. Bestenlehner et al. 2011, A&A 530, L14
46. http://cochise.astro.psu.edu/30dor/chandra_data/extract/point_sources.noindex/VFTS682/
47. http://www2.astro.psu.edu/xray/acis/acis_analysis.html