DIFFUSE, NON-THERMAL X-RAY EMISSION FROM THE GALACTIC STAR CLUSTER WESTERLUND 1

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ABSTRACT

We present the diffuse X-ray emission identified in Chandra observations of the young, massive Galactic star cluster Westerlund 1. After removing point-like X-ray sources down to a completeness limit of $\approx 2 \times 10^{31}$ erg s$^{-1}$, we identify $(3 \pm 1) \times 10^{34}$ erg s$^{-1}$ (2–8 keV) of diffuse emission. The spatial distribution of the emission can be described as a slightly-elliptical Lorentzian core with a half-width half-maximum along the major axis of $5'' \pm 1''$, similar to the distribution of point sources in the cluster, plus a 5’ halo of extended emission. The spectrum of the diffuse emission is dominated by a hard continuum component that can be described as a $kT \approx 3$ keV thermal plasma that has a low iron abundance ($\lesssim 0.3$ solar), or as non-thermal emission that could be stellar light that is inverse-Compton scattered by MeV electrons. Only 5% of the flux is produced by a $kT \approx 0.7$ keV plasma. The low luminosity of the thermal emission and the lack of a 6.7 keV iron line suggests that $\lesssim 40,000$ unresolved stars with masses between 0.3 and $2M_\odot$ are present in the cluster. Moreover, the flux in the diffuse emission is a factor of two lower than would be expected from a supersonically-expanding cluster wind, and there is no evidence for thermal remnants produced by supernovae. Less than $10^{-5}$ of the mechanical luminosity of the cluster is dissipated as 2–8 keV X-rays, leaving a large amount of energy that either is radiated at other wavelengths, is dissipated beyond the bounds of our image, or escapes into the intergalactic medium.

Subject headings: X-rays: stars, ISM — stars: winds — supernova remnants — star clusters: individual (Westerlund 1)

1. INTRODUCTION

Sensitive X-ray observations are an increasingly important tool for studying young star clusters, particularly now that the Chandra X-ray Observatory and the Newton X-ray Multi-Mirror Mission have made harder X-rays (2–10 keV) available for study. Young stars of all types are strong X-ray sources, with low-mass ($M < 3M_\odot$) pre-main-sequence stars producing X-rays in their active magnetic coronae (Preibisch & Feigelson 2003; Feigelson et al. 2003), and massive OB stars ($M \gtrsim 8M_\odot$) producing X-rays through shocks in their stellar winds (Chlebowski & Garmany 1991; Berghöfer et al. 1993; Skinner et al. 2002). Therefore, using observations of local star forming regions (e.g., Orion) as templates, measurements of the integrated X-ray luminosities of more distant clusters can be used to constrain their total stellar population, including the numbers of young stars that may be unobservable in the optical and infrared because of extinction or source confusion (Feigelson et al. 2003; Nayakshin & Sunyaev 2003).

X-ray observations of clusters of massive stars also reveal diffuse X-ray emission that is produced as stellar winds encounter each other and the surrounding interstellar medium (ISM; e.g., Stevens & Hartwell 2003; Townsley et al. 2003; Townsley et al. 2005b, 2006). Learning the fate of the energy carried by these winds, and eventually by supernovae, would provide insight into how galaxies evolve. If the energy is transferred to the ISM, it might at first trigger future generations of star formation, but a sufficiently large input of energy could clear away the ISM and halt star formation. Alternatively, if the energy escapes a galaxy, stellar winds and supernovae would enrich the intergalactic medium with metals. To determine the fate of that energy, it is necessary to obtain X-ray observations of clusters that have a range of ages and populations, and that are surrounded by ISM with a variety of densities (e.g., Townsley et al. 2003, 2005b).

In this paper, we report on Chandra observations of the diffuse X-ray emission from the young Galactic star cluster Westerlund 1. The cluster contains 24 Wolf-Rayet (WR) stars, more than 80 blue super-giants, at least 3 red super-giants, a luminous blue variable, and an amazing 6 yellow hyper-giants, only 6 of which are known in the entire rest of the Galaxy (Westerlund 1987; Clark & Negueruela 2002, 2004; Negueruela & Clark 2003; Clark et al. 2005). Assuming a standard initial mass function (Kroupa 2002), Westerlund 1 could be as massive as $10^5 M_\odot$, making it several times larger than the well-known, young Galactic clusters the Arches, Quintuplet, and NGC 3603. Westerlund 1 is also located only $\approx 5$ kpc away (Clark & Negueruela 2002; Clark et al. 2005), so it is one of the closest young, dense star clusters. Therefore,
Westerlund 1 is a crucial object for understanding the evolution of star clusters, and their impact on the ISM of their host galaxies.

This is one of several papers describing the Chandra observations. In Muno et al. (2006), we reported the detection of a slow X-ray pulsar in Westerlund 1. Skinner et al. (2006) examined the X-ray emission from the Wolf-Rayet (WR) stars in the cluster, as well as a subset of the OB supergiants that are brightest in X-rays. In Clark et al. (in prep.), we will report the spectroscopic identification of further optical counterparts to the X-ray sources, and discuss the origin of the X-ray emission from these stars. In this paper, we describe the spatial distribution (§2.1) and spectrum (§2.2) of the diffuse X-rays. We compare the emission seen from Westerlund 1 to that of other massive star clusters in the Local Group (§3). We suggest that Westerlund 1 is one of only a few star clusters to produce mostly non-thermal X-rays. We discuss the contraints that this places on the contributions of pre-main-sequence stars (§3.1), stellar winds (§3.2), and supernovae (§3.3) to the diffuse emission, and examine what could be causing non-thermal emission (§3.4).

2. OBSERVATIONS AND DATA ANALYSIS

Westerlund 1 was observed with the Chandra X-ray Observatory Advanced CCD Spectrometer Spectroscopic array (ACIS-S; Weisskopf et al. 2002) on two occasions: on 2005 May 22 for 18 ks (sequence 5411), and on 2005 June 20 for 42 ks (sequence 6283). We reduced the observation using standard tools that are part of CIAO version 3.3. We first created a composite event list for each observation and then searched for intervals during which the background rate flared to \( \geq 3\sigma \) above the mean level, and removed one such interval lasting 3.6 ks from sequence 5411. The composite image of the full field is displayed in Clark et al. (in prep.); Figure 1 displays the inner 10′ of the cluster at 1″ resolution.

As described in Clark et al. (in prep.), we identified point-like X-ray sources in each observation using a wavelet-based algorithm, wavdetect (Freeman et al. 2002). In order to examine the diffuse X-ray emission, we then removed events that fell within circles circumscribing approximately 92% of the PSF at the location of each point source, and created an image using the remaining photons. Within 5′ of the cluster core, 7386 counts were associated with known point sources, and 38,350 counts in diffuse emission, so photons from point sources in the wings of the point spread function contribute only 0.5% to the diffuse flux.

2.1. Spatial Distribution

The signal-to-noise in a 1″ pixel was low, so we adaptively binned the image using the Weighted Voronoi Tessellation algorithm implemented by Diehl & Statler (2000), which is based on the algorithm of Cappellari & Copin (2003). The resulting image is displayed in the right panel of Figure 1.

In order to quantify the extent of the diffuse emission, we modeled its adaptively-binned, two-dimensional spatial distribution (Figure 1) as a Lorentzian function. Other functional forms used to model the light from star clusters also may be consistent with the data (e.g., Elson, Fall, & Freeman 1987, Anders, Gieles, & de Grijs...
However, there is little tradition in modeling the spatial distribution of diffuse X-rays from star clusters with analytic functions, because that emission usually has a complex morphology (e.g., Townsley et al. 2003), so there is not an obvious choice for a functional form. We chose a Lorentzian function for its simplicity, and because it is similar to the King models often used to quantify the distribution of optical light from star clusters (King 1962). The diffuse emission from Westerlund 1 is not circularly symmetric, so we allow for an elliptical distribution defined as

\[ f(x', y') = C \frac{N}{1 + (x'^2 + e^2y'^2)/r_0^2}, \]

where \(x' = (\alpha - \alpha_0) \cos \delta_0 \cos \theta + (\delta - \delta_0) \sin \theta\) and \(y' = (\delta - \delta_0) \cos \theta - (\alpha - \alpha_0) \cos \delta_0 \sin \theta\). Here, \(\alpha_0\) and \(\delta_0\) are the center of the distribution and \(x'\) and \(y'\) are the offset in arcseconds from the center, where the axes defining them have been rotated east of north by \(\theta\) degrees. The remaining parameters are the background count rate \(C\), the peak count rate \(N\), the ellipticity of the distribution \(\epsilon\) (a value of 1 implies a circle), and the characteristic radius of the distribution \(r_0\). The final parameters and the goodness-of-fit \(\chi^2/\nu\) are listed in Table 2.

Guided by Figure 2, we extracted spectra, response functions, and effective area curves for a circular 1' region around the cluster center, and annular regions 1'-2', 2'-3.5', and 3.5'-5' from the cluster center. The background-subtracted spectra are displayed in Figure 3 in units of detector counts per square arcminute.

The spectra contained contributions from at least three sources of X-rays: plasma and unresolved stars in the Galactic plane, and events produced by particles incident on the detectors. The spectrum of the background from particles has been well-characterized using observations in which the ACIS detectors were stowed out of the focal plane. Therefore, we subtracted the spectrum of the particle background from our source spectra. However, we were not able to make a local estimate of the Galactic emission, because the cluster emission extended over the entire image. We have not attempted to subtract the Galactic plane emission from the spectra of the diffuse emission from Westerlund 1, but have estimated the contribution of the Galactic emission by modeling a spectrum from observations of the diffuse emission from Westerlund 1 in the 1.5-8 keV energy range, for two reasons. First, the mean absorption column measured from the X-ray spectra of the point sources in Westerlund 1 is equivalent to named part of an elliptical Lorentzian, including some bright knots of emission at the center of the cluster, and a ridge of emission extending to the southeast toward the X-ray pulsar reported by Muno et al. (2006), it is also labeled in Fig. 1. However, the model does provide a useful means to quantify the azimuthally-averaged distribution of the emission, as can be seen in the radial distribution, plotted in units of \(r' = (x'^2 + e^2y'^2)^{1/2}\), in Figure 2. The half-width half-maximum of the distribution is \(25\pm1''\), which for a distance of 5 kpc corresponds to 0.5 pc. The widths of the distributions of both optical stars and point-like X-ray sources are also \(25''\) (Clark et al. 2005; Muno et al. 2006). Moreover, the centroid of the diffuse emission lies within the \(5''\) uncertainty in the centroid of the point sources, (Muno et al. 2006), although it is \(20''\) from the centroid of the optically-detected stars (Piatti, Bica, & Claria 1998; Clark et al. 2004). The discrepancy could be caused either by differential extinction toward the cluster, or by substructure in the cluster (J. S. Clark et al., in prep.).

In Figure 2, we have also indicated the amount of flux expected from the background of particles impacting the detector (\(1.5 \times 10^{-9} \) ph cm\(^{-2}\) s\(^{-1}\)), and the mean flux taken from observations of the Galactic plane at \(l = 28^\circ\) and \(b = 0.2^\circ\) (\(2.2 \times 10^{-9} \) ph cm\(^{-2}\) s\(^{-1}\)), of which half was particle background; see Ebisawa et al. (2005). Even 5' from the cluster core, 60% of the flux was from Westerlund 1, so there is a broad halo of diffuse X-rays around the cluster. In contrast, although a few O stars that are cluster members are located beyond \(\sim 3'\) from the cluster core (Clark et al. 2005), the surface density of X-ray point sources beyond 3' is consistent that of the Galactic disk (Muno et al. 2006), so there is no similar halo of point-like X-ray sources.

### 2.2. Spectra

Guided by Figure 2, we extracted spectra, response functions, and effective area curves for a circular 1' region around the cluster center, and annular regions 1'-2', 2'-3.5', and 3.5'-5' from the cluster center. The background-subtracted spectra are displayed in Figure 3 in units of detector counts per square arcminute.

The spectra contained contributions from at least three sources of X-rays: plasma and unresolved stars in the Galactic plane, and events produced by particles incident on the detectors. The spectrum of the background from particles has been well-characterized using observations in which the ACIS detectors were stowed out of the focal plane. Therefore, we subtracted the spectrum of the particle background from our source spectra. However, we were not able to make a local estimate of the Galactic emission, because the cluster emission extended over the entire image. We have not attempted to subtract the Galactic plane emission from the spectra of the diffuse emission from Westerlund 1, but have estimated the contribution of the Galactic emission by modeling a spectrum from observations of a field at \(l = 28^\circ\) and \(b = 0.2^\circ\) (Ebisawa et al. 2001, 2005).

We modeled the emission using version 12.2.0 of XSPEC (Arnaud et al. 1996). We chose to model only the 1.5-8 keV energy range, for two reasons. First, the mean absorption column measured from the X-ray spectra of the point sources in Westerlund 1 is equivalent to
$2 \times 10^{22} \text{ cm}^{-2}$ of hydrogen (J. S. Clark et al., in prep.). Therefore, most of the observed X-ray flux from the cluster should emerge at energies above $\sim 2$ keV, and the lower-energy X-rays are probably from foreground emission. Second, given that the diffuse emission from Westerlund 1 is probably from several different sources, we do not have enough physical guidance to extrapolate our models below 2 keV. When we try to apply simple models, the inferred de-reddened 0.5–2.0 keV flux can span an order-of-magnitude depending upon the model assumptions. The lower bound was chosen to include the prominent line at 1.8 keV in the spectra from the inner 2$'$ of the cluster. For consistency with the other works quoted in §3, we report the observed and de-reddened 2–8 keV fluxes.

We first attempted to model the spectrum as a single temperature thermal plasma, either in or out of collisional ionization equilibrium, absorbed by the interstellar medium. We found that those simple models provided a poor description of the data from the inner 2$'$ of the cluster ($\chi^2/\nu \geq 1.5$).

Therefore, we modeled the spectra as an absorbed, two-temperature thermal plasma. Most of the 4–8 keV continuum flux could be modeled as a hot plasma with $kT_2 \gtrsim 3$ keV. In the inner 3.5$'$ of the cluster, the presence of emission lines near 1.8 keV from He-like Si and 2.3 keV from He-like S indicated that some of the flux is produced by a cool $kT_1 \lesssim 1$ keV plasma. The metal abundances in the cooler component were poorly constrained because it contributes very little to the continuum emission, so we fixed the metal abundances to the mean best-fit value of $Z/Z_{\odot} = 2$. Moreover, the spectrum taken from the 3.5–5.0$'$ annulus lacked obvious line emission, so the parameters of any cool plasma emission were unconstrained. Therefore, we omitted the cool component from the model of that spectrum. In Table 2, we list the parameters of the best-fit, two temperature, collisional ionization equilibrium models; using non-equilibrium models yields similar results for the derived temperatures and abundances. Using these as-
Diffuse X-rays from Westerlund 1

**TABLE 2**

**TWO-TEMPERATURE PLASMA MODEL FOR THE DIFFUSE X-RAY EMISSION**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$&lt;1'$</th>
<th>1–2'</th>
<th>2.0–3.5'</th>
<th>3.5–5.0'</th>
</tr>
</thead>
<tbody>
<tr>
<td>counts</td>
<td>4250</td>
<td>6679</td>
<td>12698</td>
<td>14714</td>
</tr>
<tr>
<td>background</td>
<td>698</td>
<td>2244</td>
<td>5613</td>
<td>6636</td>
</tr>
<tr>
<td>area (arcmin$^2$)</td>
<td>2.7</td>
<td>8.9</td>
<td>25.6</td>
<td>34.9</td>
</tr>
<tr>
<td>$N_H$ (10$^{22}$ cm$^{-2}$)</td>
<td>2.2$^{-0.2}_{+0.2}$</td>
<td>2.0$^{-0.2}_{+0.2}$</td>
<td>2.3$^{-0.2}_{+0.2}$</td>
<td>2.4$^{-0.2}_{+0.2}$</td>
</tr>
<tr>
<td>$kT_1$ (keV)</td>
<td>0.71$^{-0.1}_{+0.08}$</td>
<td>0.7$^{-0.1}_{+0.1}$</td>
<td>1.6$^{-0.2}_{+0.2}$</td>
<td>...</td>
</tr>
<tr>
<td>$Z_1$/Z$_\odot$</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>...</td>
</tr>
<tr>
<td>$\int n_e n_H dV$ (cm$^{-6}$ pc$^3$)</td>
<td>2.2</td>
<td>6.2</td>
<td>6.2</td>
<td>...</td>
</tr>
<tr>
<td>$kT_2$ (keV)</td>
<td>3.2$^{-0.4}_{+0.5}$</td>
<td>5.7$^{+1.2}_{-1.0}$</td>
<td>11$^{+2.2}_{-1.4}$</td>
<td>6.8$^{+0.9}_{-0.8}$</td>
</tr>
<tr>
<td>$Z_2$/Z$_\odot$</td>
<td>&lt;0.4</td>
<td>&lt;0.3</td>
<td>0.6$^{-0.5}_{+0.2}$</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>$\int n_e n_H dV$ (cm$^{-6}$ pc$^3$)</td>
<td>10$^{-3}_{+3}$</td>
<td>17$^{+1}_{-2}$</td>
<td>24$^{+2}_{-2}$</td>
<td>43$^{+3}_{-3}$</td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>73.4/65</td>
<td>80.4/72</td>
<td>104.9/101</td>
<td>129.1/116</td>
</tr>
</tbody>
</table>

**Note.** — Uncertainties are 1σ, found by varying each parameter until $\Delta \chi^2 = 1.0$. $uF_{X,1}$ and $uF_{X,2}$ are the de-absorbed 2–8 keV flux from the thermal and non-thermal components of the spectral model, respectively. If we extrapolate our models to the 0.5–2.0 keV band, the rapidly-increasing contribution from the $kT=0.7$ keV thermal plasma causes the inferred X-ray luminosity to be a factor of 2–3 larger. Note also that at 5 kpc, 1 arcmin = 1.45 pc.

**TABLE 3**

**THERMAL PLUS NON-THERMAL MODEL FOR THE DIFFUSE X-RAY EMISSION**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$&lt;1'$</th>
<th>1–2'</th>
<th>2.0–3.5'</th>
<th>3.5–5.0'</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H$ (10$^{22}$ cm$^{-2}$)</td>
<td>2.7$^{0.3}_{-0.2}$</td>
<td>2.3$^{0.3}_{-0.2}$</td>
<td>2.4$^{+0.2}_{-0.2}$</td>
<td>2.8$^{+0.3}_{-0.2}$</td>
</tr>
<tr>
<td>$kT_1$ (keV)</td>
<td>0.68$^{+0.1}_{-0.08}$</td>
<td>0.68$^{+0.13}_{-0.1}$</td>
<td>1.1$^{+0.2}_{-0.1}$</td>
<td>...</td>
</tr>
<tr>
<td>$Z_1$/Z$_\odot$</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>...</td>
</tr>
<tr>
<td>$\int n_e n_H dV$ (cm$^{-6}$ pc$^3$)</td>
<td>11$^{+4}_{-3}$</td>
<td>7$^{+1.8}_{-0.8}$</td>
<td>6$^{+2}_{-2}$</td>
<td>...</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>2.7$^{+0.2}_{-0.1}$</td>
<td>2.1$^{+0.2}_{-0.2}$</td>
<td>1.7$^{+0.1}_{-0.1}$</td>
<td>2.0$^{+0.2}_{-0.1}$</td>
</tr>
<tr>
<td>$N_T$ (10$^{-3}$ ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$)</td>
<td>1.0$^{+0.3}_{-0.0}$</td>
<td>0.7$^{+0.1}_{-0.1}$</td>
<td>0.8$^{+0.1}_{-0.1}$</td>
<td>1.7$^{+0.2}_{-0.2}$</td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td>70.4/66</td>
<td>80.4/73</td>
<td>107.2/102</td>
<td>132.2/116</td>
</tr>
<tr>
<td>$F_X$ (10$^{-13}$ erg cm$^{-2}$ s$^{-1}$)</td>
<td>7.2$^{+0.7}_{-0.7}$</td>
<td>11.7$^{+1.0}_{-1.0}$</td>
<td>23.1$^{+2.0}_{-2.0}$</td>
<td>28.0$^{+2.0}_{-2.0}$</td>
</tr>
<tr>
<td>$uF_{X,1}$ (10$^{-13}$ erg cm$^{-2}$ s$^{-1}$)</td>
<td>1.6</td>
<td>1.0</td>
<td>2.2</td>
<td>...</td>
</tr>
<tr>
<td>$uF_{X,2}$ (10$^{-13}$ erg cm$^{-2}$ s$^{-1}$)</td>
<td>9.0</td>
<td>14.2</td>
<td>27.2</td>
<td>37.3</td>
</tr>
</tbody>
</table>

**Note.** — See Table 2.

The most notable trend in the cool components is that their contributions to the spectra decline from 15% in the central 1', to 7% between 1' and 3.5', finally becoming undetectable beyond 3.5' from the cluster center. Otherwise, the inferred interstellar absorption remains roughly constant near $2.6 \times 10^{22}$ cm$^{-2}$, the temperature of the thermal component is constant near $kT=0.7$–1 keV. We find that the temperature of the hot plasma increases from $kT=3$ keV at the cluster center, to a maximum 11 keV in the 2.0–3.5' annulus, and then decreases to 6 keV in the outer annulus. The relative lack of flux near the He-like Fe line at 6.7 keV in most of the spectra implies that the iron abundances are less than half of the solar values. Interestingly, similar sub-solar iron abundances are inferred from the lack of 0.8–1.0 keV Fe L lines from several known Galactic Wolf-Rayet and O stars (e.g., Skinner et al. 2001, 2002; Schulz et al. 2003; Skinner et al. 2005).

Alternatively, the lack of line emission near 6.7 keV could be explained if much of the continuum X-ray emission is non-thermal. Therefore, we have also modeled the emission as the sum of emission from a $kT<1$ keV thermal plasma and a power law (Table 3). The metal abundances in the cooler component were once again fixed to $Z/Z_\odot=2$, and we omitted the cool component from the model of the 3.5–5' annulus. This provides an equally good description of the data as the two-temperature plasma model, and the same trends are evident: the contribution of the cool component declines monotonically with offset from the cluster center, and the overall spectrum becomes harder.

The contributions of each model component under the second set of models are indicated in Figure 8 using dotted lines for the thermal plasma, and dashed lines for the
power law component. We also display the spectrum of the Galactic ridge emission at $l = 28^\circ$ and $b = 0.2^\circ$ (grey data points). The line emission from the Galactic flux is a bit stronger than that from Westerlund 1, but otherwise the spectra are fairly similar. Therefore, we cannot completely rule out the hypothesis that the emission beyond $\lesssim 2^\circ$ from the cluster core is Galactic. However, our assumption that the diffuse emission is from Westerlund 1 is conservative. As described in §3, we find that the luminosity of diffuse X-rays from Westerlund 1 is much lower than expected, and assuming that the diffuse halo is Galactic would exacerbate the discrepancy.

The total, de-reddened 2–8 keV flux from within 5′ of Westerlund 1 is $9.3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. By varying the assumptions in our model, we find that the systematic uncertainty in the 2–8 keV flux is $\approx 20\%$. Based on the Chandra observations taken at $l = 28^\circ$ and $b = 0.2^\circ$ (see also Ebisawa et al. 2003), we expect the Galactic emission to be $3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$ (2–8 keV; see also Hands et al. 2004). Therefore, within 5′ of the core of Westerlund 1 the Galactic plane contributes $\approx 20\%$ to the inferred flux. Subtracting this foreground and background emission, and using a distance to Westerlund 1 of 5 kpc (Clark et al. 2003), we find that the luminosity of the diffuse X-ray emission from the cluster is $(3 \pm 1) \times 10^{-14}$ erg s$^{-1}$ (2–8 keV). Only $\approx 5\%$ of this luminosity is from the $\lesssim 1$ keV thermal component.

3. DISCUSSION

The origin of the diffuse X-ray emission from clusters of massive young stars is currently under debate. Several authors (e.g., Cantó, Raga, & Rodríguez 2000; Stevens & Hartwell 2003) have modeled the diffuse X-rays from the most massive clusters in the Local Group as a cluster wind. Under this model, the winds of individual stars collide, thermalize, and form a pressure-driven bulk flow that expands supersonically into the interstellar medium (Chevalier & Clegg 1985). Stevens & Hartwell (2003) tabulated results from studies of R136, NGC 3603 (Moffat et al. 2002), NGC 346 (Názé et al. 2002), the Rosette (Townsley et al. 2003), and the Arches (Yusef-Zadeh et al. 2002), and showed that the luminosities of their diffuse X-ray emission $(1 - 6) \times 10^{34}$ erg s$^{-1}$ were considerably larger than would be expected from the standard cluster wind model. The large X-ray luminosities can be explained in several ways: the densities of the cluster winds could be higher than expected because the stellar winds entrained cooler material or because radiative losses decreased the temperature of the shocked plasma (Stevens & Hartwell 2003); the wind energy could be dissipated through heat conduction where it encounters nearby molecular clouds (Dorland & Montmerle 1987); or the wind could be confined by the surrounding ISM (Chu et al. 1993). Alternatively, the large X-ray luminosities might partly result from the fact that unresolved pre-main-sequence stars should contribute significantly to the luminosity of the (apparently) diffuse emission, especially for more distant clusters (e.g., Townsley et al. 2008).

Westerlund 1 is at least as massive as NGC 3603, R136, and the Arches (Clark et al. 2005), so from an observational standpoint the luminosity of its diffuse X-rays $(3 \pm 1) \times 10^{34}$ erg s$^{-1}$; 2–8 keV) is understandable. However, the spectrum and spatial distribution of the diffuse X-ray emission from Westerlund 1 presents more of a puzzle. First, the spectrum lacks the line emission from He-like Fe that would be expected from a thermal plasma given the hard continuum flux. In contrast, the spectra of pre-main sequence stars exhibit prominent lines from He-like and H-like Si, S, Ar, and Fe that imply metal abundances up to ten times the solar value (e.g., Feigelson et al. 2002). However, X-ray spectra of O and WR stars often exhibit weak Fe emission that imply abundances $\lesssim 0.3$ solar (e.g., Skinner et al. 2001; Schulz et al. 2003; Skinner et al. 2004), so it is possible that the diffuse flux is dominated by plasma from the O and WR star winds, with little contribution from pre-main-sequence stars. It is also possible that the diffuse emission is non-thermal, by analogy with similar interpretations for the hard flux from a handful of young stellar associations, including RCW 38 (Wolk et al. 2002), DEM L192 (N51D; Cooper et al. 2003), 30 Dor C (Bamba et al. 2004), and possibly the Arches cluster (Law & Yusef-Zadeh 2004). In most of the above cases, the non-thermal emission has been interpreted as synchrotron emission from supernova remnants. We will examine this hypothesis for Westerlund 1 in §8.

The second surprise is that the diffuse X-ray emission from Westerlund 1 seems to extend far beyond the core of the cluster. Within the inner 2′, the surface brightness of the diffuse emission falls off with a half-width half-maximum of 0.5 pc (Fig. 1 and 2), which is identical to the distribution of point-like X-ray sources (Clark et al., in prep). This core of diffuse emission could be produced either from the cluster wind, which radiates X-rays mostly in the region where the colliding winds are thermalized (Stevens & Hartwell 2003), or from an unresolved population of pre-main-sequence stars. However, between 2′ and 5′ (3–7 pc) from the cluster core the diffuse X-ray flux attains a constant level $\approx 7 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$ (Tab. 2 Fig. 1), which is 2–3 times larger than is expected from the Galactic plane (e.g., Hands et al. 2004; Ebisawa et al. 2005). An expanding thermal plasma would exhibit a rapidly-declining temperature profile, yet the spectrum of this halo of diffuse emission is quite hard and lacks the line emission expected from a cooling plasma. This makes it tempting to interpret the diffuse halo as non-thermal particles that are accelerated in a large-scale outflow.

Therefore, although the luminosity of the diffuse X-ray emission from Westerlund 1 is not surprising, the lack of line emission in the spectrum and broad spatial distribution of the diffuse X-rays is. To address this, in the following sections we quantify the probable contributions of pre-main-sequence stars, stellar winds, and supernovae to the X-ray emission from Westerlund 1.

3.1. Unresolved Low-Mass Stars

The non-thermal spectrum of the diffuse X-ray emission from Westerlund 1 puts interesting constraints on the population of low-mass stars in the cluster. The average spectrum of the lightly-absorbed pre-main-sequence stars in Orion can be qualitatively described as a two-temperature plasma with $kT_1 = 0.5$ keV and $kT_2 = 3.3$ keV, and with metal abundances of up to 10 times solar for S, Ar, Ca, and Fe (Feigelson et al. 2002). In contrast, in our models for the diffuse emission from Westerlund
1, a kT<1 keV plasma contributes only 5% of the 2–8 keV diffuse X-ray flux, and the remaining hard flux does not exhibit the expected He-like Fe line at 6.7 keV, placing an upper limit on the Fe abundance of ≤0.3 solar (Tab. 2). To obtain a conservative estimate of the number of low mass stars in the cluster, we assume that they have solar Fe abundances (i.e., much lower abundances than the stars in Orion). We find that they produce ≲30% of the diffuse flux from Westerlund 1, or ≈9 × 10^{33} erg s^{-1} (2–8 keV).

We use the results of the Chandra Orion Ultradeep Project (COUP) to convert this luminosity into a number of low-mass stars, taking into account the difference in ages between the two clusters. For Orion, the 1398 stars later than B4 in the COUP observations have an integrated, de-absorbed 2–8 keV luminosity of 1.2 × 10^{33} erg s^{-1} (Reigelson et al. 2005). Most of this emission is produced by stars with 0.3 < M < 3 M_⊙. However, the stars in Westerlund 1, with ages of ≈4 Myr (Clark et al. 2007), are significantly older than the 1-Myr-old population in Orion. To take this into account, we first note that when 2–3 M_⊙ stars reach an age of ≈4 Myr, they become fully radiative and their X-ray luminosities drop by an order of magnitude (Flaccomio et al. 2003). Even though they are only 5% of low-mass stars by number, in Orion these 2–3 M_⊙ stars produce ≈30% of the flux from 0.3 < M < 3 M_⊙ stars (see Fig. 4, in Reigelson et al. 2005), or ≈8 × 10^{32} erg s^{-1}. Second, Preibisch & Feigelson (2003) find that the X-ray luminosities of young stars with 0.5 < M < 2 M_⊙ fall off with time as L_x ∝ t^{-0.75}, so at 4 Myr the stars in Orion should be ≈3 times fainter. Therefore, if Orion were 4 Myr old, we would expect its ≈1400 stars with 0.3 < M < 2 M_⊙ to have a luminosity of 3 × 10^{32} erg s^{-1} (2–8 keV). Our upper limit to the integrated X-ray luminosity of low-mass stars in Westerlund 1 is ≲9 × 10^{33} erg s^{-1}, so we infer that Westerlund 1 contains ≲40,000 stars with masses between 0.3 < M < 2 M_⊙.

This number of low-mass stars is smaller than one would expect if one were to extrapolate from the number of massive, post-main-sequence stars in the cluster using a standard initial mass function (Kroupa 2002). There are ≈150 stars brighter than V = 21 within 5’ of the center of Westerlund 1, the faintest of which have recently been identified as O7 main sequence stars that would have initial masses ≳30 M_⊙ (J. S. Clark et al. in prep). The maximum initial mass of the stars remaining in the cluster is uncertain because there is no precise means to determine the initial masses of the supergiants and WR stars, but Clark et al. (2005) argue that it is probably in the range of 40–50 M_⊙. If we assume that the initial mass function can be described as a broken power law of the form dN ∝ M^{-α}dM, where α = 2.3 for M > 0.5 M_⊙ and α = 1.4 for 0.3 < M < 0.5 M_⊙ (Kroupa 2002), then if there are 150 stars with 30 < M < 50 M_⊙, we would expect 100,000 stars with 0.3 < M < 2 M_⊙. This inferred lack of low-mass stars can be explained several ways. The slope of the initial mass function could be flat (α > 2.1), as has been inferred for NGC 3603 and the Arches cluster based on infrared star counts (e.g., Eisenhauer et al. 1998; Stolte et al. 2005). The mass function could be truncated at low masses (M < 0.6 M_⊙), by analogy with the fact that M > 7 M_⊙ stars appear to be depleted in the Arches cluster (Stolte et al. 2005). Finally, the initial masses of the post-main sequence stars in Westerlund 1 could span a much wider range of masses (20–60 M_⊙) than assumed in Clark et al. (2005).

If we assume that the mass function is truncated at low masses, the total mass of the cluster would not differ significantly from the estimate of 10^9 M_⊙ in Clark et al. (2005) based on the un-modified Kroupa form. However, if the mass function is flat, or the optically-detected stars had a wider range of initial masses, the total mass of the cluster would be only 40,000–70,000 M_⊙. Obviously, an accurate measurement of the mass function, and consequently the total mass, requires direct infrared observations of the low-mass stars in Westerlund 1. However, these X-ray observations provide a useful starting point.

### 3.2. Stellar Winds

It is not clear whether stellar winds or supernovae are the dominant source of the diffuse X-ray emission from Westerlund 1, because it is at an age when both should contribute equally to its mechanical output (e.g., Leitherer, Robert, & Drissen 1992). Individual stellar winds carry a power of

\[ L_w = 3 \times 10^{35} \left( \frac{M}{10^{-6} M_\odot/yr} \right) \left( \frac{v_w}{10^3 \text{ km/s}} \right)^2 \text{ erg s}^{-1}, \]

(2)

where \( M \) is the mass loss rate, and \( v_w \) is the wind velocity. The WR stars dominate the mechanical output from stellar winds, with typical \( M \approx 6 \times 10^{-5} M_\odot \text{ yr}^{-1} \) and \( v_w \approx 1700 \text{ km s}^{-1} \), so that \( L_w \approx 5 \times 10^{37} \text{ erg s}^{-1} \) (Leitherer et al. 1992). With at 24 WR stars in the cluster, the total mechanical energy output from winds is \( > 1 \times 10^{39} \text{ erg s}^{-1} \).

We can estimate the X-ray luminosity of the resulting cluster wind using the analytic solutions to the density and temperature that Cantó et al. (2000) see also Stevens & Hartwell 2003) derived for a wind expanding supersonically into the interstellar medium (Chevalier & Clegg 1985). Within the radius of the cluster where the stars input their energy, the density is given by

\[ n_0 = 0.1 N \left( \frac{M_w}{10^{-5} M_\odot/yr} \right) \left( \frac{v_w}{10^3 \text{ km/s}} \right)^{-1} \left( \frac{R_c}{\text{ pc}} \right)^{-2} \text{ cm}^{-3} \]

(3)

(note that we used the supersonic solution with an adiabatic index \( \gamma = 5/3 \) for the original equation) and the temperature by

\[ kT_0 = 1.3 \left( \frac{v_w}{1000 \text{ km/s}} \right)^2 \text{ keV}, \]

(4)

where \( N \) is the number of stars, \( M_w \) is the average mass loss rate of the stars, and \( R_c \) is the radius within which the stars are contained and the winds are thermalized. If we use the values above for WR stars, assume \( N = 24 \), and take the radius of the cluster to be \( R_c = 4 \text{ pc} \) (≈3′ at 5 kpc), then we find \( n_0 = 0.6 \text{ cm}^{-3} \) and \( kT_0 = 4 \text{ keV} \). Using any of the standard plasma models.
in XSPEC (e.g., Meew, Lemen, & van den Oord 1986; Liedahl, Osterheld, & Goldstein 1995), and converting \( n_0 \) and \( R_e \) to an emission measure (i.e., \( K_{\text{EM}} = \pi R_e^2 n_0^2 \)) we find a predicted \( L_X = 3 \times 10^{34} \) erg s\(^{-1}\) (2.8 keV).

Therefore, a cluster wind could in principle account for all of the diffuse X-rays from Westerlund 1.

However, the cluster wind model is not able to account for the spatial distribution of the diffuse X-rays from Westerlund 1. A cluster wind would produce almost all of the diffuse X-ray emission within the core radius \( R_e \) (Stevens & Hartwell 2003), whereas at 70% of the diffuse emission from Westerlund 1 is part of a halo that extends out to at least 5′ (Fig. 2). If consider only the core of the diffuse emission as originating from stellar winds, then the cluster is underluminous by a factor of two.

This result is particularly surprising given that the standard cluster wind model applied by Stevens & Hartwell (2003) to NGC 3203, R136, and NGC 346 predicted significantly less flux than is observed. In those cases, Stevens & Hartwell (2003) favored the hypothesis that cold material was being entrained in the wind. To reconcile our results for Westerlund 1 to the cluster wind model, we would have to assume that enough cold material is entrained that the cluster wind no longer emits in the 2–8 keV bandpass. This requires that the plasma be cooled by a factor of \( \approx 10 \), to \( < 0.4 \) keV. Based on Figure 1 in Stevens & Hartwell (2003), we estimate that this would require the mass of cold material input into the wind to be twice that of the hot material, or roughly \( 3 \times 10^{-3} M_\odot \) yr\(^{-1}\). The mass loss rates from the \( \approx 10 \) luminous blue variables, red supergiants, and yellow hypergiants, which should be \( < 10^{-4} M_\odot \) yr\(^{-1}\) each (e.g., Jura & Kleinmann 1994; Leitherer et al. 1992; Smith, Vink, & de Koter 2004), probably could not account for this large amount of cool mass. Therefore, either there is a currently-unseen source of mass in Westerlund 1, or the stellar winds are not thermalized within the cluster and escape without radiating much.

3.3. Supernovae

The presence of an isolated X-ray pulsar in Westerlund 1 (Muno et al. 2006) confirms that supernovae have occurred there. If we extrapolate an initial mass function with slope \( \alpha = 1.8–2.7 \) for \( M > 30 M_\odot \) to higher masses, we expect that the cluster originally contained \( \approx 80–150 \) stars with initial masses \( > 50 M_\odot \) that have already undergone supernova. For the most massive stars, this would have started when the cluster was about 3 Myr old, so the average supernova rate over the last 1 Myr should be on order one every 7,000–13,000 yr. If each supernova had a kinetic energy of \( 10^{51} \) erg, then the average power released by supernovae is \( \sim (2–5) \times 10^{39} \) erg s\(^{-1}\).

No obvious supernova remnant is present in our Chandra image of Westerlund 1, but this is not surprising. We have examined images from the Spitzer GLIMPSE program (R. Indebetouw, private communication), and there is no evidence that dense gas or dust still surrounds Westerlund 1. Therefore, Westerlund 1 appears to have cleared away the ISM for parsecs around. When a supernova occurs in such an evacuated cavity, a typical radio and X-ray remnant is not expected until the remnant encounters the boundaries of the bubble blown by the cluster (e.g., Ciotti & D’Eccel 1989).

Whether the hard, possibly non-thermal emission from Westerlund 1 is produced by supernovae is unclear. Most supernova remnants produce thermal X-ray emission with strong lines, but a few are also non-thermal X-ray sources. For example, RCW 86 and SN 1006 exhibit non-thermal filaments near the outer boundary of the shock, and thermal emission in the interior (e.g., Dyer, Reynolds, & Borkowski 2004; Rio et al. 2002). AX J1843.8–0352 and G346.3-0.5 exhibit non-thermal emission almost exclusively throughout the remnant (e.g., Ueno et al. 2003; Lazendic et al. 2005; Hiraga et al. 2003). Unfortunately, there is not a satisfactory explanation as to why a small fraction of supernova remnants produce non-thermal emission, so the issue remains unresolved for Westerlund 1.

3.4. Non-Thermal Particles

In principle, non-thermal particles can be produced either in supernova remnants (e.g., Livnytkov & Pohl 2004) or in colliding stellar winds (e.g., Eichler & Usov 1993). Once they are produced, inverse-Compton scattering should dominate synchrotron losses by a large factor in Westerlund 1 (see, e.g., Rybicki & Lightman 1979). The ratio of the energy-loss rates is given by the ratio of the background radiation to the magnetic energy density. The energy density of the stellar light from the OB and WR stars in Westerlund 1 is approximately

\[
U_{\text{phot}} = \frac{L_{\text{stars}}}{4\pi c D^2} = 5.5 \times 10^{-9} \left( \frac{L_{\text{stars}}}{10^7 L_\odot} \right) \left( \frac{d}{1 \text{ pc}} \right)^{-2} \text{ erg cm}^{-3}\tag{5}
\]

where \( L_{\text{stars}} \sim 10^7 L_\odot \) the luminosity of the cluster. For synchrotron losses to be important, magnetic fields would have to have an energy of \( B^2/8\pi \gtrsim U_{\text{phot}} \), which corresponds to \( B \gtrsim 0.4 \) mGauss. This is much stronger than the microGauss fields generally assumed for the interstellar medium (e.g., Beck 2001), so inverse-Compton scattering is probably the dominant loss mechanism for non-thermal particles.

If the non-thermal X-ray emission is produced by inverse-Compton scattering, the energy requirements are modest. Non-thermal particles would only need to be replenished at a rate sufficient to balance the X-ray luminosity, \( 3 \times 10^{34} \) erg s\(^{-1}\). Furthermore, inverse-Compton scattering photons from optical and UV energies (\( E_{\text{in}} = 2–20 \) eV) into the X-ray band (\( E_{\text{out}} \approx 3 \) keV) only requires electrons with \( \gamma^2 \sim E_{\text{out}}/E_{\text{in}} \), or energies of 6–20 MeV. These particle energies are rather small. For comparison, if the magnetic field in Westerlund 1 has a strength of only 10 \( \mu \)Gauss, producing non-thermal synchrotron radio emission like that seen from 30 Dor C (Bamba et al. 2004) requires electrons with energies of a few GeV. Therefore, detecting diffuse, low-thermal radio emission from a star cluster like Westerlund 1 (e.g., Yusef-Zadeh et al. 2003) would provide a much more interesting constraint on the maximum eneriges of particles than detecting non-thermal X-rays. The interferometric radio observations in the literature (Clark et al. 1998) would have resolved out arcminute-scale diffuse radio emission, so single-dish observations are necessary to...
fewer than the 10^5 objects. Therefore, we infer that there are \( \lesssim 4 \times 10^5 \) stars with masses between 0.3 and 2 M\(_\odot\), which is significantly fewer than the 10^5 stars one would expect from extrapolating the number of massive, optically-identified stars to lower masses using a standard initial mass function (Clark et al. 2005). Moreover, this limit is conservative, because in computing it we have assumed that the line emissivities for Research in Astronomy, Inc., for NASA, under contract NAS8-03060. Support for MPM was provided by NASA through Hubble Fellowship grant HST-HF-01164.01-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555.

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