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A NEUTRON STAR WITH A MASSIVE PROGENITOR IN WESTERLUND 1

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ABSTRACT

We report the discovery of an X-ray pulsar in the young, massive Galactic star cluster Westerlund 1. We detected a coherent signal from the brightest X-ray source in the cluster, CXO J164710.2–455216, during two *Chandra* observations on 2005 May 22 and June 18. The period of the pulsar is 10.6107(1) s. We place an upper limit to the period derivative of $\dot{P} < 2 \times 10^{-10}$ s s^{-1}, which implies that the spin-down luminosity is $\dot{E} \leq 3 \times 10^{33}$ erg s^{-1}. The X-ray luminosity of the pulsar is $L_{\rm X} \approx 3^{+10}_{-2} \times 10^{33} (D/5~{\rm kpc})^2$ erg s^{-1}, and the spectrum can be described by a $kT = 0.61^{+0.02}_{-0.02}$ keV blackbody with a radius of $R_{\rm bb} = 0.27 \pm 0.03 (D/5~{\rm kpc})$ km. Deep infrared observations reveal no counterpart with $K<18.5$, ruling out a binary companion with $M>1M_\odot$. Taken together, the properties of the pulsar indicate that it is a magnetar. The rarity of slow X-ray pulsars and the position of CXO J164710.2–455216 only 1.6′ from the core of Westerlund 1 indicates that it is a member of the cluster with >99.97% confidence. Westerlund 1 contains 07V stars with initial masses $M_i \approx 35 M_\odot$ and >50 post-main-sequence stars that indicate the cluster is 4±1 Myr old. Therefore, the progenitor to this pulsar had an initial mass $M_i > 40 M_\odot$. This is the most secure result among a handful of observational limits to the masses of the progenitors to neutron stars.

Subject headings: X-rays: stars — neutron stars — open clusters and associations: individual (Westerlund 1)

1. INTRODUCTION

Most of our knowledge about the masses of the progenitors to neutron stars is based on theoretical calculations (e.g., Heger et al. 2003). Quantitative observational constraints are difficult to establish. The few previous, tentative estimates have relied on inferring these masses from traces of the interactions of the progenitors with their surroundings (Nomoto et al. 1982; MacAlpine et al. 1989; Gaensler et al. 2005), on developing scenarios by which individual accreting X-ray binaries could have formed (e.g., Ergma & van den Heuvel 1998; Wellstein & Langer 1999), or on demonstrating that the progenitor was a member of a population of coeval stars with well-determined masses (e.g., Fuchs et al. 1999; Vrba et al. 2000; Figer et al. 2005; Pellizza et al. 2005). The first two methods remain uncertain because of their dependence on assumptions in the relevant models. The third class of results are potentially the most reliable, although there is sometimes debate over the whether the neutron stars and the stellar associations are related (e.g., Cameron et al. 2005; McClure-Griffiths & Gaensler 2005).

Here we report the discovery of a neutron star in *Chandra* observations of the Galactic star cluster Westerlund 1. The cluster contains an exceptional population of >50 massive, post-main-sequence stars that are only 4±1 Myr old (Westerlund 1987; Clark et al. 2005). Its total mass of $>10^5 M_\odot$ is contained in a region only ≈9 pc across, which suggests that the stars were born in a single episode of star formation (Clark et al. 2005). This makes it an ideal cluster for placing limits on the initial masses of progenitors to compact objects.

2. OBSERVATIONS AND DATA ANALYSIS

We observed Westerlund 1 with the *Chandra X-ray Observatory* Advanced CCD Spectrometer Spectroscopic array (ACIS-S)Weisskopf et al. (2002) on two occasions: 2005 May 22 for 18 ks (sequence 5411) and 2005 June 18 for 42 ks (sequence 6283). The event lists were reduced using the standard tools and techniques described on the web site of the *Chandra X-ray Center* (CXC).

We used the wavelet-based algorithm `wavdetect` (Freeman et al. 2002) to identify 238 individual point-like X-ray sources in the entire image (which covered approximately four times the area displayed in Fig. 1). Half of these sources are located in the central portion of the image shown. Above our completeness limit of 6×10^{-7} ph cm^{-2} s^{-1} (0.5–8.0 keV), we find that the central surface density of X-ray sources is 33^{+16}_{-10}

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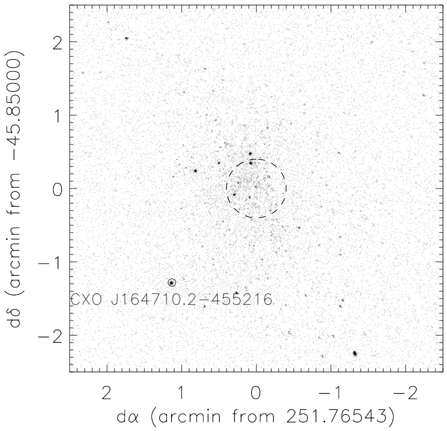

FIG. 1.— The central 5′×5′ of the image we obtained of Westerlund 1 with *Chandra*. The image is a composite of two exposures, taken on 2005 May 22 and June 18. The count image has been corrected to account for the varying exposure across the image. We have indicated the centroid and core-radius of the cluster derived from the locations of the X-ray sources using the dashed line. The location of the pulsar is indicated with the solid circle.

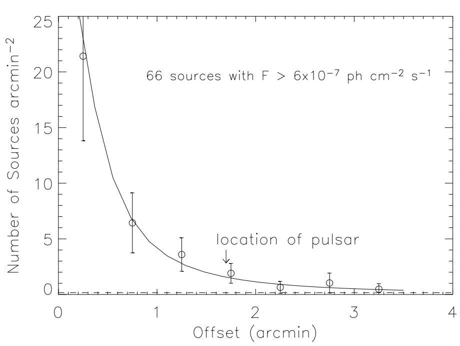

FIG. 2.— The binned radial distribution of point sources brighter than our 50% completeness limit. The distribution is computing assuming that its centroid is at α,δ = 16 47 03.7, −45 51 00 (J2000). The solid line is the best-fit Lorentzian model of the *unbinned* distribution, which has a width of $\theta_0 = 0.4 \pm 0.1$ arcmin and a central surface density of $\rho_0 = 33^{+16}_{-10}$ sources arcmin^{-2}.

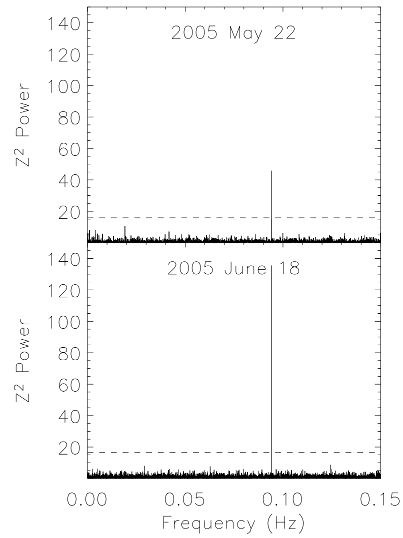

FIG. 3.— The periodogram of CXO J164710.2–455216, which is the only source to exhibit a significant periodic signal. The dashed lines denote the powers above which there is a <1% chance that noise would produce signals that large. The signal from CXO J164710.2–455216 produced $Z_1^2 = 58.3$ from 398 counts in the May observation, and $Z_1^2 = 135$ from 857 events in the June observation. The periodicity was significant at the $>8\sigma$ level. The profile of the signal was sinusoidal, and the fractional rms amplitudes were 53.0(1)% and 54.91(3)%.

arcmin^{-2}. For comparison, observations of the Galactic plane at $l = 28°$ and $b = 0.2°$ reveal only 0.17±0.04 sources arcmin^{-2} at this flux level (e.g., Ebisawa et al. 2001). The surface density of sources can be modeled as a Lorentzian function with half-width 0.4±0.1 arcmin (Fig. 2). Therefore, even without considering the properties of individual X-ray sources, any one located within 1.′7 of the core of Westerlund 1 has a >90% chance of being a cluster member.

Most of the X-ray sources have Wolf-Rayet or O (WR/O) stars as counterparts in optical or infrared images, and are probably colliding-wind binaries. However, some of the WR/O stars could be in binaries with accreting compact objects, and X-ray sources without obvious stellar counterparts could be isolated pulsars. We did not find any obvious candidates for accreting black holes (J. S. Clark et al., in prep).

The best means of identifying neutron stars is to search for rotationally-modulated X-ray emission. Therefore, for the brightest sources, we adjusted the arrival times of their photons to the Solar System barycenter and computed Fourier periodograms using the Rayleigh statistic (Z_1^2; Bucceri et al. 1983). The individual X-ray events were recorded with a time resolution of 3.2 s, so the Nyquist frequency was ≈0.15 Hz, which represents the limit below which our sensitivity could be well-characterised. However, we computed the periodogram using a maximum frequency of ≈0.6 Hz, to take advantage of the limited sensitivity to higher frequency signals, and to ensure that any observed signal was not an alias. We searched the two observations separately, so that a search for signals from a single source required 3221 independent trials for the May observation, and 6239 trials for the June observation. The corresponding single-source detection threshold powers for 99% confidence in each observation are Z_1^2=12.7 and 13.3, respectively, where the powers have been normalised so that Poisson noise produces power with a mean value of 1. This power can be related to the root-mean-squared (rms) amplitude of a sinusoidal signal by $A = (2Z_1^2/N_\gamma)^{1/2}$, where N_γ is the number of photons from the source. A fully-modulated signal would have an amplitude of 0.71, so the minimum number of counts required to detect a signal are N_γ=51 and 53, respectively. We searched 8 sources above this count limit in the May observation, and 16 sources in the June observation.

One periodic signal from the brightest X-ray source in the field, CXO J164710.2–455216 (α,δ = 251.79250,–45.87136 [J2000], ±0.′′3 with 90% conf.), significantly exceeded the expected noise in both observations (Fig. 3). We refined an initial estimate of the period by computing pulse profiles from non-overlapping 5000 s intervals during each observation, and modelling the dif-

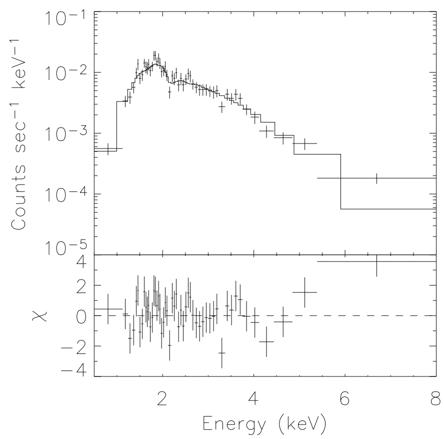

FIG. 4.— The X-ray spectrum of CXO J164710.2–455216. The top panel displays the spectrum in detector counts as a function of energy, so the shape of the source spectrum is convolved with the detector response. Several models reproduced the data equally well (see text). The bottom panel contains the difference between the data and the best-fit black body model, divided by the Poisson uncertainty on the data points.

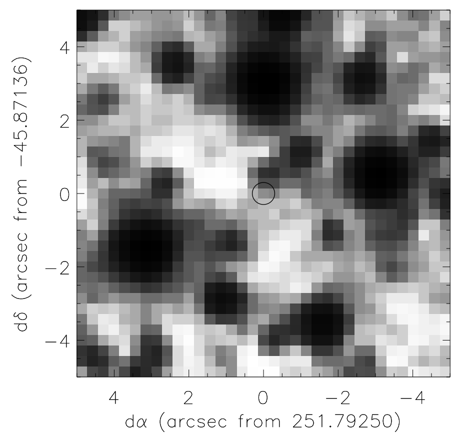

FIG. 5.— Infrared image a $10'' \times 10''$ field around CXO J164710.2–455216. The image was taken with the ESO/NTT in the K_s band, and is composed of 10×1.2s images obtained on 2003 June 19 (P.I.: J. Alves). The circle denotes the 0.″3 uncertainty (90% confidence) in the location of the X-ray source. An object with an intensity of K_s=18.4±0.3 mag lies 0.″5 from the X-ray source. This source is near the detection limit, and chance that it is associated with the pulsar ≈1.5%. The upper limit on the intensity of any object within the error circle is K_s>18.5.

ferences between the assumed and measured phases using first-and second-order polynomials. The reference epochs of the pulse maxima for the two observations were 53512.860265(4) and 53539.67325(2) (MJD, TBD). The best-fit periods were 10.6112(4) s and 10.6107(1) s for 2005 May and June, respectively. This placed a limit on the difference in period between the two observations of $\Delta P < 0.5$ ms, or on the period derivative of $\dot{P} < 2 \times 10^{-10}$ s s^{-1}. From the quadratic fits to the phases during the individual May and June observations, we found $\Delta P < 2$ and < 0.4 ms ($\dot{P} < 9 \times 10^{-8}$ s s^{-1} and $< 1 \times 10^{-8}$ s s^{-1}), respectively. Unfortunately, there was a ≈2 cycle ambiguity when trying to predict the phases over the month interval between observations, so the period cannot be refined further using the current observations. Nonetheless, the stability of the signal from CXO J164710.2–455216 suggests that it is produced by the rotation of neutron star.

We extracted spectra of CXO J164710.2–455216 using standard tools and the acis_extract routine.[13] We found no evidence that the intensity of the source changed between May and June, so we combined the spectra obtained from both observations. We modeled the spectrum using XSPEC version 12 (Arnaud 1996). All uncertainties were computed using 1σ confidence intervals ($\Delta\chi^2$=1). The spectrum could be described equally well ($\lesssim$10% chance probability) by black body, bremsstrahlung, or power law continuum models that were absorbed and scattered by the interstellar medium (ISM). To facilitate comparisons with other isolated neutron stars, we report the parameters of black body model ($\chi^2/\nu = 63.8/49$), for which we derive an absorption column of $N_{\rm H} = 1.2 \pm 0.1 \times 10^{22}$ cm^{-2}, a best-fit temperature of $kT = 0.61 \pm 0.02$ keV, and an apparent radius of $R_{\rm bb} = 0.27 \pm 0.03 (D/5$ kpc) km.

Comparing the three continuum models, we found that the interstellar extinction toward the source is $N_{\rm H} = (1.2 - 2.6) \times 10^{22}$ cm^{-2}. This is consistent with the range measured for other cluster members, $N_{\rm H} = [1.4 - 2.9] \times 10^{22}$ cm^{-2}, where the dispersion can be accounted for by variable extinction caused by a foreground molecular cloud (see Clark et al. 2005). The observed flux was $F_{\rm X} = 2.4^{+0.2}_{-0.6} \times 10^{-13}$ erg cm^{-2} s^{-1} (0.5–8.0 keV). We de-reddened the three models, and found $L_{\rm X} = 3^{+10}_{-2} \times 10^{33} (D/(5\ {\rm kpc})^2$ erg s^{-1} (0.5–8 keV).

To evaluate whether CXO J164710.2–455216 is an accreting system, we searched for an infrared counterpart in K_s-band images taken with the SofI instrument on the ESO New Technology Telescope (Fig. 5). There was no counterpart to the pulsar within the 0.″3 uncertainty in its location (90% confidence). The upper limit to its intensity was K_s≥18.5, ruling out a companion with M>1 $M_\odot$ (Girardi et al. 2002). For comparison, the faintest stars that have contracted onto the main sequence in Westerlund 1 have M_i=2$M_\odot$ (Brandner et al., in prep.).

3. DISCUSSION

The spectrum and luminosity of CXO J164710.2–455216 (Fig. 4) demonstrate that it is not a conventional radio pulsar. First, the power lost as the pulsar spins down is too small to produce the observed X-ray emission. Assuming that it is a 10 km, 1.4$M_\odot$ neutron star ($I \sim 10^{45}$ g cm^2), the upper limit to the period derivative ($\dot{P} < 2 \times 10^{-10}$ s s^{-1}) implies that the spin-down energy is $\dot{E} = 4\pi I \dot{P}/P^3 \leq 3 \times 10^{33}$ erg s^{-1}. This is similar to the observed X-ray luminosity, whereas magnetospheric emission from a radio pulsar with $\dot{E} \leq 10^{35}$ erg s^{-1} would produce $L_{\rm X} < 10^{-3}\dot{E}$ (Cheng, Taam, & Wang 2004). Second, the X-ray emission is inconsistent with thermal emission from a young, cooling neutron star. Although the characteristic temperature of the emission (kT≈0.6 keV) is consistent with the high end of the range expected for cooling neutron stars (e.g., Yakovlev & Pethick 2004), the lumi-

[13] http://www.astro.psu.edu/xray/docs/TARA/

nosity is 100 times lower than would be expected if the surface of the neutron star had a uniform temperature.

In contrast, the X-ray emission is consistent with that of highly-magnetized ($B>3\times10^{14}$ G), slowly rotating pulsars, which are referred to as magnetars (Duncan & Thomspon 1992). Known magnetars have spin periods between 5 and 12 s, $L_X=10^{33}-10^{36}$ erg s^{-1}, and spectra that peak at ≈2 keV (e.g., Mereghetti et al. 2004; Woods & Thompson 2005).

The X-ray emission is also consistent with that from faint, wind-accreting neutron stars, such as A 0535+26 (P=104 s; Orlandini et al. 2004), X Per (P=837 s; Di Salvo et al. 1998; Delgado-Martí et al. 2001) and 4U 0115+63 (P=3.6 s; Campana et al. 2001). However, forming a close, accreting binary from a system that initially contained two stars with $M>40M_\odot$ (see below) and $M<1M_\odot$ would present a significant challenge to models for producing low-mass X-ray binaries (e.g., Portegies-Zwart, Verbunt, & Ergma 1997). Therefore, we suspect that CXO J164710.2–455216 is a magnetar.

It is likely that CXO J164710.2–455216 is associated with Westerlund 1, because Galactic X-ray pulsars with P=3–30 s are rare (only ≈20 known; Liu et al. 2000). To evaluate the chance that this pulsar is a random Galactic object unassociated with Westerlund 1, we attempted to determine the surface density of slow X-ray pulsars on the sky. Previous searches for X-ray pulsars were biased toward the most luminous X-ray sources, so we searched ≈350 fields in the Galactic plane ($-5<b<5°$) that were observed with *Chandra* and *XMM-Newton*. Aside from ≈15 known examples that were the targets of the relevant observations, we found no new pulsars with P=3–30 s (A. Nechita et al., in prep). Therefore, the chance of discovering a slow X-ray pulsar in any pointing is $\lesssim$0.3%. (We note that the ≈15 known slow X-ray pulsars within the more conservative latitude range of $|b|<1°$ have a surface density of ∼0.03 degree^{-2}. The ACIS-S FOV is ≈0.07 degree^{-2}, which also implies that the chance of finding a slow pulsar in a *Chandra* observation is ∼0.2%.) Moreover, CXO J164710.2–455216 lies only 1.′7 from the center of Westerlund 1 (2.3[D/5 kpc] pc in projection). Based on the spatial distribution of X-ray sources described above, a source at that location has a ∼10% chance of being a random association. We conclude that this pulsar is a member of Westerlund 1 with ∼99.97% confidence.

The fact that CXO J164710.2–455216 is member of Westerlund 1 places a lower limit on the initial mass of its progenitor. Clark et al. (2005) have established that the cluster is only 4±1 Myr old, so that the minimum mass of a star that could have undergone a supernova is ≈40 $M_\odot$. This is supported by the identification of several O7–O8V stars in the cluster, which have zero-age main sequence masses of 34–37 $M_\odot$ (J. S. Clark et al., in prep.). Therefore, CXO J164710.2–455216 was produced by a star with $M_i>40M_\odot$.

Previously, only three secure lower limits were obtained on the masses of progenitors to neutron stars, all of which were for magnetars. First, a shell of HI around 1E 1048.1–5937 was interpreted as ISM displaced by the wind of a progenitor with M_i=30–40$M_\odot$(Gaensler et al. 2005). Second, SGR 1900+14 was suggested to be a member of a star cluster <10 Myr old (Vrba et al. 2000), placing a lower limit on the progenitor mass of $M_i\gtrsim20M_\odot$. Finally, SGR 1806–20 was claimed to be a member of a star cluster that is only $\lesssim$4.5 Myr old (although see Cameron et al. 2005; McClure-Griffiths & Gaensler 2005), providing a limit of $M_i\gtrsim50M_\odot$(e.g., Fuchs et al. 1999; Figer et al. 2005). Our evidence that CXO J164710.2–455216 also descended from a star with $M_i>40$ $M_\odot$ dispels much of the doubt that the previous results represented chance associations.

These results demonstrate that some stars with $M_i>40$ $M_\odot$ do not collapse into black holes at the ends of their lives, but instead form neutron stars. This implies that massive stars can lose ≥95% of their mass either before or during supernovae. Before supernovae, stars could lose mass through strong winds (e.g., Heger et al. 2003) or be stripped of mass by binary companions (e.g., Wellstein & Langer 1999). During supernovae, rapidly-rotating cores could drive mass away through magneto-hydrodynamic winds (e.g., Akiyama & Wheeler 2005). To determine the importance of these effects, it is necessary to identify additional neutron stars in star clusters and constrain the masses of their progenitors.

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