New Astronomy 16 (2011) 461–469

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Diffuse thermal X-ray emission in the core of the young massive cluster Westerlund 1

P.J. Kavanagh [a,b,*], L. Norci [a,b], E.J.A. Meurs [c,a]

[a] School of Physical Sciences, Dublin City University, Dublin 9, Ireland
[b] National Centre for Plasma Science and Technology, DCU, Dublin 9, Ireland
[c] School of Cosmic Physics, Dublin Institute for Advanced Studies, Dublin 2, Ireland

ARTICLE INFO

Article history:
Received 5 October 2010
Received in revised form 18 March 2011
Accepted 4 April 2011
Available online 9 April 2011
Communicated by M. van der Klis

Keywords:
Open clusters and associations
Individual (Westerlund 1)
X-rays: general
Stars: Pre-Main Sequence
Stars: winds
Outflows

ABSTRACT

We present an analysis of the diffuse hard X-ray emission in the core of the young massive Galactic cluster Westerlund 1 based on a 48 ks XMM-Newton observation. Chandra results for the diffuse X-ray emission have indicated a soft thermal component together with a hard component that could be either thermal or non-thermal. We seek to resolve this ambiguity regarding the hard component exploiting the higher sensitivity of XMM-Newton to diffuse emission. Our new X-ray spectra from the central (2′ radius) diffuse emission are found to exhibit He-like Fe 6.7 keV line emission, demonstrating that the hard emission in the cluster core is predominantly thermal in origin. Potential sources of this hard component are reviewed, namely an unresolved Pre-Main Sequence population, a thermalized cluster wind and Supernova Remnants interacting with stellar winds. We find that the thermalized cluster wind likely contributes the majority of the hard emission with some contribution from the Pre-Main Sequence population. It is unlikely that Supernova Remnants are contributing significantly to the Westerlund 1 diffuse emission at the current epoch.

1. Introduction

Since their launch in 1999, the Chandra and XMM-Newton observatories have revolutionized the study of X-ray emission from stellar clusters. Chandra's ACIS and XMM-Newton's EPIC have allowed unprecedented analysis of point sources and diffuse emission in such objects. Of particular importance are the observations of extragalactic Super Star Clusters (SSCs). SSCs[1] are young (1–10 Myr), massive (10^5–10^7 $M_\odot$) objects with extremely dense cores ($\lesssim 10^5$ $M_\odot$ pc^{-3}) and are the predominant sites of massive star formation in starburst and interacting galaxies (e.g. NGC 4038/39 and M82, Whitmore et al., 1999; Melo et al., 2005). However SSCs are not limited to these extreme environments, with some found in objects such as Blue Compact Dwarfs, non-interacting spirals and Ultra Luminous Infrared Galaxies (e.g. Henize 2–10 and PKS 1345+12-C1: Johnson et al., 2000; Larsen and Richtler, 1999; Rodríguez Zaurín et al., 2007). Apart from hosting large numbers of massive stars, SSCs also serve to enrich and energize the local Interstellar Medium (ISM) through a shocked outflowing cluster wind. The cluster wind arises from interacting stellar winds from the massive star population and later from SN ejecta. The enrichment of the local ISM by the cluster wind can potentially drive further star formation in the region. In dwarf starburst galaxies, these winds may be powerful enough to produce a galactic outflow, enriching the Intergalactic Medium (IGM) and potentially killing further star formation in the galaxy. Hence, SSCs provide not only a laboratory for the study of massive stars at various stages of evolution but can also provide vital insights into cluster evolution and star formation on large scales. Unfortunately, given the distance to many of these SSCs and their extremely compact nature it is often impossible to resolve the diffuse emission from the point source emission using Chandra or XMM-Newton. However, it is possible to resolve the diffuse and point source emission in local lower mass analogues. Thus, detailed analysis of such nearer objects can provide key insights to the inner workings of SSCs. Westerlund 1 (Wd1) is one such cluster, which holds the distinction of being the most massive young cluster in the Galaxy.

Wd1 was discovered in the early sixties and was initially classified as an open cluster (Westerlund, 1961). The cluster suffers from significant reddening ($A_V \approx 12.9$ mag, Piatti et al., 1998) and, because of this, only recently detailed photometric and spectroscopic analyses have been performed (Clark and Negueruela, 2002, 2004; Negueruela and Clark, 2005; Clark et al., 2005). Clark et al. (2005) found a rich population of evolved OB stars and, using a standard Kroupa (Kroupa, 2001) initial mass function (IMF), inferred a

* Corresponding author at: School of Physical Sciences, Dublin City University, Dublin 9, Ireland. Fax: +353 1 7005384.
E-mail address: patrick.kavanagh8@mail.dcu.ie (P.J. Kavanagh).

[1] We note that there exists some ambiguity in the literature as to the classification of SSCs. We follow here one of the many sets of classification criteria, as in Whitmore (2000).

1384-1076/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.newast.2011.04.001

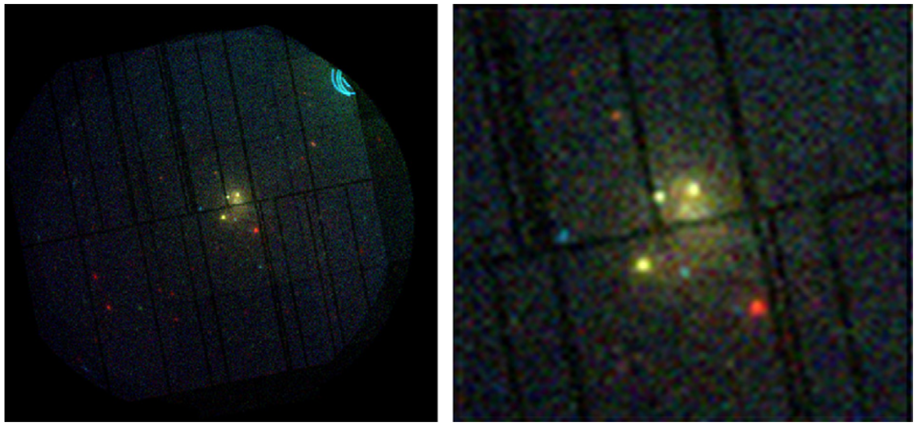

Fig. 1. Combined MOS/PN false colour images of Westerlund 1 with red, green and blue corresponding to the 0.3–2 keV, 2–4.5 keV and 4.5–10 keV energy bands, respectively. North is up, East is left. Left panel: The entire FOV, approximately 30′ in diameter. Both the Wd1 cluster diffuse emission and several point sources are seen at the centre with additional sources scattered throughout the FOV. The X-ray binary 4U 1642–45 reflection artifact is seen in the upper right of the image. Right panel: 5′ × 5′ region centered on Westerlund 1 highlighting the cluster diffuse emission. The bright soft source to the southwest (seen in red) is the foreground star HD 151018, an O9Iab star.

cluster mass of $\gtrsim 10^5\,M_\odot$. This is at the lower limit of the SSC mass range and certainly made Wd1 the most massive cluster in the Galaxy. A more recent deep IR study, however, revises this mass estimate somewhat downwards to $\approx 4.5 \times 10^4\,M_\odot$ (Brandner et al., 2008). Although this is still bigger than any other known Galactic cluster, it is slightly smaller than extragalactic SSCs. The same study also revised previous estimates of age and distance to 3.6 ± 0.7 Myr and 3.55 ± 0.17 kpc, respectively, which we adopt for our analysis. Muno et al. (2006), henceforth MU06, used Chandra data to perform a diffuse emission analysis and found that the emission throughout the cluster is dominated by a hard component. However, they were unable to identify the nature of this emission due to the absence of hard emission lines and discussed both thermal and non-thermal origins for the hard component.

In this paper we seek to resolve this issue using the XMM-Newton observational data, given the telescopes' greater sensitivity to diffuse emission. As yet these data have only been used in an analysis of the well known magnetar CXOU J164710.2-455216 in this cluster (Muno et al., 2006, 2007). In Section 2 we outline the observational data reduction, before briefly discussing the point source analysis in Section 2.1. We follow by presenting the detailed diffuse emission analysis in Section 2.2. In Section 3 we discuss our results before offering our conclusions in Section 4.

2. Observations and analysis

XMM-Newton observed Wd1 on 16 September 2006 for ∼48 ks (Obs. ID 0404340101, Revolution 1240). The event files were processed using the XMM-Newton Science Analysis Software (SAS, Version 7.1.0) meta-tasks *emproc* and *epproc*. We then filtered the data for good grades in the energy band 0.3–10 keV (the energy range at which all 3 of the EPIC instruments are most sensitive) and created images for each of the three EPIC cameras, namely the PN, MOS1 and MOS2. The PN and MOS2 images were found to contain single reflection artifacts which are due to X-rays from a source outside the field of view (20′–80′ off-axis) reaching the sensitive area of the focal plane detectors by single reflection from the rear end of the hyperboloid component of the XMM-Newton mirror shells.[2] This object was identified as the low mass X-ray binary 4U 1642-45 which is located approximately 20′ to the northwest of the observation aimpoint. Images from the three EPIC instruments were combined to produce the false colour image shown in Fig. 1.

2.1. Point sources

Point source detection was performed over three standard XMM-Newton energy bands (0.5–2 keV, 2–4.5 keV and 4.5–7.5 keV) on the three EPIC images using the SAS meta-task *edetect-chain*. In total, 90 sources with a minimum maximum-likelihood detection threshold of 10 were found; 7 of these are associated with the reflection and were thus ignored. A further 8 sources were flagged as spurious due to their positions on or near chip gaps and were removed from consideration, leaving 75 source detections in the field. By correlation with the comprehensive Chandra source list in Clark et al. (2008), 4 of our XMM-Newton sources appear to have high mass stellar X-ray emitting counterparts in the cluster with a further 8 having Pre-Main Sequence (PMS) stellar objects. One other source in the cluster area (within 5′ of the cluster centre, Muno et al., 2006) was found to have no counterpart in the source list of Clark et al. (2008) or in the SIMBAD database and is likely a newly detected flaring PMS star. Table 1 gives our detected cluster sources and their corresponding Chandra designations, along with spectrally derived source parameters.

2.2. Diffuse analysis

It is obvious from Fig. 1 not only that the reflections could contaminate the diffuse emission in Wd1 but also that they are more prominent in the harder energies which are of particular interest to our analysis. To address this we considered various analysis techniques including the XMM-Newton Extended Source Analysis Software (ESAS) and 'blank sky' background event files but found that none could adequately account for the reflection emission. Instead we opt for the more traditional method of background extraction from regions within the FOV. By defining background regions that are as contaminated by the reflection as the cluster, the contribution of the reflection to the cluster spectra can be reduced. We decided against using the PN data for the diffuse emission analysis as several detector gaps mask some of the Wd1 cluster core. Therefore, the following analysis is based on the MOS data only. To assess first the diffuse emission in the FOV of the MOS cameras we create a non-background subtracted image of the emission using ESAS

[2] See http://xmm.esa.int/external/xmm_user_support/documentation/uhb/node23.html.