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RADIO OBSERVATIONS OF THE MASSIVE STELLAR CLUSTER WESTERLUND 1

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RESUMEN

Se presentan observaciones de radio de alto rango dinámico hacia Westerlund 1 (Wd 1), que permiten detectar un total de 21 estrellas en el cúmulo estelar joven y masivo, el cual tiene la más rica población de radioestrellas conocida dentro de los cúmulos estelares jóvenes galácticos. Discutiremos algunos de los objetos más notables, incluyendo la estrella supergigante B[e] identificada como W9, muy luminosa en radioondas, y que presenta una tasa de pérdida de masa estimada ($\sim 10^{-3}\ M_{\odot}\ \mathrm{yr}^{-1}$) comparable a la de η Carina, junto con la detección algo inusual de emisión térmica de casi todas las supergigantes rojas e hipergigantes amarillas. Hay evidencia en rayos X importante para proponer que cada una de las estrellas WR con emisión en radio es probablemente un sistema binario con vientos en colisión.

ABSTRACT

High-dynamic range radio observations of Westerlund 1 (Wd 1) are presented that detect a total of 21 stars in the young massive stellar cluster, the richest population of radio emitting stars known for any young massive galactic cluster in the Galaxy. We will discuss some of the more remarkable objects, including the highly radio luminous supergiant B[e] star W9, with an estimated mass-loss rate ($\sim 10^{-3}\ M_{\odot}\ \mathrm{yr}^{-1}$) comparable to that of η Carina, along with the somewhat unusal detection of thermal emission from almost all the cool red supergiants and yellow hypergiants. There is strong supporting evidence from X-ray observations that each of the WR stars with radio emission are likely to be colliding-wind binaries.

Key Words: open clusters and associations: individual (Westerlund 1) — radio continuum: stars — stars: individual (W9)

1. INTRODUCTION

Wd 1 is a highly reddened ($A_v \sim 12$ mag), compact galactic cluster discovered by Westerlund (Westerlund 1961), and now known to have a unique population of post-main sequence massive stars with representative members of all evolutionary stages: OB supergiants and hypergiants, red and yellow supergiants, and Wolf-Rayet stars (Clark & Negueruela 2002; Clark et al. 2005). With a total stellar mass likely in excess of $10^5\ M_{\odot}$ (Clark et al. 2005), Wd 1 is more massive than any of the other massive galactic clusters, and has comparable mass to Super Star Clusters (SSC), previously identified only in other galaxies. If Wd 1 is an SSC within our own Galaxy, it presents a unique opportunity to study the properties of a nearby SSC, where it is possible to resolve the individual members of the cluster population, and determine basic properties that are difficult in the typically more distant examples.

Radio observations were obtained at four frequencies between 8.6 and 1.4 GHz with the Australia Telescope Compact Array. In addition, we obtained an R-band image from the Very Large Telescope. The optical and radio images were aligned by ensuring the peak of the optical and radio emission of the brightest source at 8.6 GHz, W9, were coincident. The resulting overlay is shown in Figure 1, and allows identification of the radio emitting objects in Wd 1.

2. RADIO STARS IN WD 1

A total of 21 stars are associated with radio emission, making Wd 1 the richest population of radio emitting stars known for any young massive galactic cluster, including the GC clusters (Lang et al. 2005) and NGC 3603 (Moffat et al. 2002). The stellar radio sources are blue, yellow or red super- or hypergiants and WR stars, representative of the different stages of massive star evolution.

The supergiant B[e] star W9 is by far the brightest stellar radio emitter in the cluster, as anticipated from a previous radio observation (Clark et al. 1998). Indeed, for a cluster distance of 4 kpc (Kothes & Dougherty 2007), W9 is one of the most radio lu-

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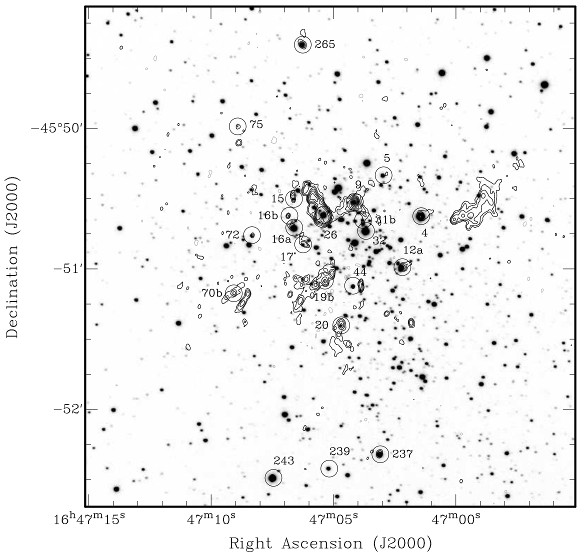

Fig. 1. 8.6-GHz emission (contours) and a FORS R-band image (greyscale). The radio sources with putative optical counterparts listed are identified by the circles and corresponding Westerlund numbers.

minous stars in the Galaxy with $L_{8\ \mathrm{GHz}} = 2 \times 10^{21}$ erg s^{-1} similar to the extreme LBV η Car at radio minimum. The radio emission of W9 is resolved into a point source and an extended component, with the former having a spectral index of $\sim +0.7$ and the extended component having a flat spectrum consistent with optically-thin thermal emission. This is interpreted as a stellar wind from the underlying star surrounded by a more extended ejection nebula. The estimated mass-loss rate is $\sim 10^{-3}\ M_\odot$/yr, unprecedented for any massive star with perhaps the exception of an LBV during outburst e.g. η Car. The striking similarities of many of the characteristics of W9 with η Car, including the discovery of an IR excess due to significant dust production, raises the intriguing possibility that W9 is an LBV with an η Car-like giant eruption happening today.

Among the cooler RSG and YHG populations in Wd 1, 5/6 of the YHGs and all four of the known RSGs are detected. Each of these objects have a spectral index consistent with optically-thin thermal emission. Being too cool to ionize their own envelopes, the stellar wind material must be ionized externally, most likely from the radiation field of the cluster, but also potentially from hot companion objects, likely another massive star. The mass of ionized material is typically $\sim 10^{-2}\ M_\odot$ for the YHGs, but among the RSGs it is as high as $\sim 1\ M_\odot$ for W26. Interestingly, the radio emission around several of the RSGs appears to have an extended, cometary morphology (e.g. W26) which may arise from ram pressure ablation due to a strong cluster wind, similar to the process underlying the similar envelope structure of the RSG IRS 7 in the Galactic Centre region e.g., Yusef-Zadeh & Morris 1991, Dyson & Hartquist 1994.

Six of the 24 known WR stars (Crowther et al. 2006) have been detected in this survey. For a mean radio derived mass-loss rate of $4 \times 10^{-5}\ M_\odot$ yr^{-1} (Leitherer et al. 1997) a flux of $(0.4 - 0.9)$ mJy is expected at a distance of 4 kpc. Even after taking into account some degree of wind clumping, we should expect to detect some WR stars in Wd 1. Each of the detected WR stars have flat spectral indices, that we suggest results from a composite spectrum of thermal and non-thermal emission, as often observed in colliding-wind binary systems (e.g. Dougherty & Williams 2000). This hypothesis is corroborated with Chandra observations of Wd 1 that show the WR stars are typically X-ray bright with $L_x \sim 10^{32-33}$ erg s^{-1} and $kT > 2.6$ keV i.e. $T > 3 \times 10^7$ K (Clark et al. 2007). Such temperatures are expected in the post-shock flow of wind-wind interaction shocks e.g., Stevens et al. (1992). The IR excess in the WC-type star W239 (WR F) has been interpreted arising from dust in a colliding-wind (Crowther et al. 2006) and together with evidence from photometric and spectroscopic observations, it appears the WR binary fraction in Wd 1 is unprecedently high, in excess of 70% (Clark et al. 2007).

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DISCUSSION

R. Barbá - Some people claim that the cluster is at the end of the MW bar. Is the rotation galactic model reliable in such a place?

S. Dougherty - This is a long answer to a good, short question. This is true. According to Benjamin et al. (2005) the central bar goes out to 4 kpc from the Galactic Centre. The distance we derive for Wd1 (3.9 kpc) puts it at a Galactocentric distance of 4.1 kpc – at the end of the bar. As for the rotation curve model, in the direction of Wd 1, the Tangent Point is at a distance of ~ 7 kpc from the Sun, at a Galactocentric radius of 2.6 kpc, within the radius of the bar. In spite of this, the rotation model we adopted assuming the distance to the galactic centre is 7.6 kpc and the circular rotation velocity of the Sun is 214 km s^{-1}, should have a radial velocity of -139 km s^{-1} at the Tangent Point. The observed value of the Tangent Point gas, seen in the HI emission profile for this direction, is between -130 and -135 km s^{-1}. This is very good agreement. Furthermore, the rotation model predicts that the Sagittarius Arm (at the far side of the Galaxy, not the near part of the Sagittarius Arm) should be at $+26$ km s^{-1}, a value very close to the HI emission peak observed at $+22$ km s^{-1}. Since this arm is outside the solar circle on the other side of the Galactic Center, this agreement is incredible, and gives us great confidence in our rotation model – in spite of the potential influence of the Bar.

H. Zinnecker - Where is the gas that has been expelled from the cluster in its HII region phase? How much is it, and is it in the form of neutral hydrogen? Is the cluster bound or expanding? Has the stellar velocity dispersion been measured?

S. Dougherty - This gas has been pushed back to the visible (in HI emission) edge of the interstellar bubble at around $0°$ latitude. It is blown out to the South, where the density falls off away from the Galactic plane. It is extremely difficult to get a reliable estimate of the mass – too much bright HI emission from the atomic gas in the Wd 1 region. It is neutral HI – or at least that is our initial interpretation of the HI image at -55 km s^{-1}. I don't know whether the cluster is bound or unbound, and I'm not sure if the dispersion has yet been measured.

P. Benaglia - As the angular resolution of the HI data is about $2'$, and the Wd 1 cluster extends up to $3'$, wouldn't you need more angular resolution to perform the HI analysis?

S. Dougherty - I don't think so. Certainly, doing the HI analysis directly using the absorption of the Wd 1 continuum was very difficult. Since Wd 1 is quite weak (~ 0.8 Jy at 21 cm) we need nearby HII regions to aid identification of the HI velocities for the Scutum-Crux Arm, before looking for any features related to Wd 1. It is important to note that the HI features we believe are associated with Wd 1 are quite large ($\sim 6'$, $12'$, and $30'$) in diameter, and the resolution is not really a problem. With higher resolution the signal-to-noise ratio of the absorption signal would increase, since Wd1 is barely resolved with a resolution of $2'$.

A. Moffat - What can one say about the co-evality of Wd 1? This is important for the question of simultaneous presence of WR and RSG's (and main sequence stars of type O7), given the upper limit of the RSG formation $m_i \approx 25\ M_\odot$ and the lower limit for WR stars of $m_i \geq 25\ M_\odot$ (as discussed earlier at the meeting).

S. Dougherty - Who said there are main sequence O7 stars ??? Not really, other than if it is not coeval. Then it really messes up any inference of the mass limit of the known AXP (Muno et al. 2006) at > 40 solar mass, based on the presence of WR stars of 25 $M_\odot$, plus any attempt at re-constructing the cluster IMF and the subsequent population evolution.

J. Groh - Can you detect radio emission from the LBV W 243? Is it thermal?

S. Dougherty - Yes we do – at both 4 and 6 cm, with upper limits at 13 and 20 cm. However, this is enough to determine a somewhat uncertain spectral index of $\alpha = +0.9 \pm 0.3$ – good enough to say that it is thermal emission.

P. Williams - Do you attach any significance to the lower rate of detection of radio emission from WC stars compared with WN stars? Many of them make dust and may be colliding-wind binaries.

S. Dougherty - No, I don't. All the WR stars we detect as isolated objects, i.e. not close to extended radio emission, have fluxes between $0.4 - 0.9$ mJy, where 0.06 mJy beam^{-1} is thermal noise. So we are only *just* detecting any of the WR stars. In total we have only detected 6 WR stars, and so any statistical inference will not be particularly sound!