Draft version June 10, 2014
Preprint typeset using LaTeX style emulateapj v. 12/16/11

MULTI EPOCH SPATIALLY RESOLVED RADIO OBSERVATIONS OF BETELGEUSE'S WIND ACCELERATION REGION

Eamon O'Gorman[1], Graham M. Harper[1], Alexander Brown[2], and Anita M. S. Richards[3]

Draft version June 10, 2014

ABSTRACT

Previous VLA observations have only spatially resolved the stellar atmosphere at 0.7 cm but here we fully resolve the star at all wavelengths between 0.7 and 6.1 cm. New multi-epoch e-MERLIN data are urgently required.

Keywords: Radio continuum: stars — Stars: supergiants — Stars: individual (α Ori) — Stars: mass-loss — Stars: winds, outflows

1. INTRODUCTION

Red supergiants (RSGs) lose mass to the interstellar medium in the form of a massive ($\dot{M} \sim 10^{-7} - 10^{-4}\, M_\odot\,\mathrm{yr}^{-1}$) cool wind, with terminal velocities ($10 \lesssim v_\infty \lesssim 50\,\mathrm{km\,s}^{-1}$) typically less than the photospheric escape velocity ($v_{\rm esc} \sim 100\,\mathrm{km,s}^{-1}$). These winds are major contributors of heavy elements to the interstellar medium and play a crucial role in stellar evolution (Chiosi & Maeder 1986), and also in explaining the frequency of supernovae in the galaxy (e.g., van Loon 2010). Despite their importance, the mechanisms responsible for the formation of these winds in late K and early M-type RSGs remain largely unknown. Dust is observed too far from the star to play a significant role in the mass-loss process (Danchi et al. 1994) and pulsation amplitudes are too low to initiate the mass-loss (Smith et al. 1989). Magnetohydrodynamic (MHD) waves (e.g., Thirumalai & Heyl 2012) and large convective cells (e.g., Josselin & Plez 2007) have been proposed as alternative potential mass-loss mechanisms in RSGs but spatially resolved multi-epoch observations of RSGs are required to test these competing theories.

Betelgeuse (α Ori, M1-2Ia-Ibe) is the closest isolated RSG at a distance of 197 ± 45 pc (Harper et al. 2008) and is therefore the prototype of the late K and early M RSG class. Its large angular diameter ($\phi_\star = 42.49 \pm 0.06$ mas in the K band, Ohnaka et al. 2011) coupled with its extended atmosphere makes its an excellent target for detailed multi-wavelength studies aiming to build a complete understanding of mass-loss in RSGs. As a result it has recently been the focus of multiple high spatial resolution studies tracing various spatial scales.

Two distinct flows in its circumstellar envelope (CSE) were imaged at 1.3 mm by **?** which traced CO($J = 2-1$) on scales between $\sim 40\,\mathrm{R}_\star$ and $\sim 750\,\mathrm{R}_\star$. These observations revealed an irregular CSE with a notable asymmetry in the S-W direction extending out to $\sim 200\,\mathrm{R}_\star$. Thermal infrared images using the VLT/VISIR ($\lambda = 8 - 20\,\mu$m, **?** detected an envelope of inhomogeneous surface brightness up to $100\,\mathrm{R}_\star$, whose spectral energy distribution is typical of oxygen-rich dust. These images also uncovered a ring-like structure at radius $20 - 45\,\mathrm{R}_\star$ which may be related to the dust condensation radius. The inner CSE was probed in the near-IR with the VLT/NACO by **?** who discovered a molecular plume extending out to almost $6\,\mathrm{R}_\star$, which they attributed to the action of a giant convection cell. Indeed Haubois et al.'s (2009) image reconstructions indicate two bright spots on the surface of Betelgeuse which may be a signature of such convective cells.

Wind acceleration zone. The wind acceleration region importance and thermal free-free as a probe. Previous radio observations (earlier VLA in agreement with ALfven models, skinner, lim, richards)

Why this paper, i.e. looking for evidence of emerlin

2. OBSERVATIONS AND DATA REDUCTION

The data were imaged within the Common Astronomical Software Application (CASA; **?**) package.
The xxx uvmodelfit was used while bounding the axis ratio between 0 and 1, and the position angle between 0 and 180.
Phase center was found using Reid & Menton

3. RESULTS

3.1. *Visibilities*

3.2. *Radio Images*

discuss fast switching (carilli paper)

3.3. *Wind Thermal Profile*

give formula

4. DISCUSSION

4.1. *Radio Flux Density Variability*

see Reid & Menton 1996 conf proceedings
see Drake conf proceedings
e-MERLIN flux is concentrated
see Harper_variability. ps
does flux go up as ang diam go up

4.2. *Structure of Wind Acceleration Region*

Thermal structure (Lim vs vs Ours vs e-MERLIN)
see Reid & Menton 1996 conf proceedings
Harper model

[1] School of Physics, Trinity College Dublin, Dublin 2, Ireland
[2] Center for Astrophysics and Space Astronomy, University of Colorado, 389 UCB, Boulder, CO 80309, USA
[3] Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK

Table 1
Multi Epoch VLA A-Configuration Plus Pie Town Link Observations of Betelgeuse.

Date	Wavelength (cm)	Restoring Beam (mas × mas)	Image rms (mJy/Beam)	$\theta_{\rm maj}$ (mas)	$\theta_{\rm maj}/\theta_{\rm min}$	P.A. (deg)	F_ν (mJy)	T_b (K)
2004 Oct 21,30	0.7	39 × 26	0.37	99 ± 3	0.93 ± 0.04	92 ± 20	28.67 ± 0.53	2940 ± 170
	1.3	80 × 42	0.09	121 ± 2	...	...	13.88 ± 0.10	3140 ± 80
	2.0	121 × 91	0.08	158 ± 6	...	...	7.23 ± 0.15	2270 ± 130
	3.6	208 × 126	0.02	215 ± 7	0.87 ± 0.04	162 ± 7	3.34 ± 0.03	2110 ± 110
	6.1	377 × 264	0.02	315 ± 30	0.59 ± 0.13	173 ± 10	1.55 ± 0.04	1140 ± 160
	20.5	1262 × 889	0.03	≤ 889	...	...	0.25 ± 0.03	>260
2003 Aug 10,12	0.7	40 × 27	0.46	103 ± 4	0.89 ± 0.06	104 ± 16	28.05 ± 0.84	2760 ± 230
	1.3	80 × 42	0.17	122 ± 5	...	...	11.20 ± 0.24	2490 ± 150
	2.0	119 × 96	0.10	132 ± 10	0.87 ± 0.10	11 ± 27	5.88 ± 0.17	3040 ± 360
	3.6	204 × 139	0.03	193 ± 7	0.73 ± 0.06	152 ± 7	2.80 ± 0.04	2610 ± 170
	6.1	378 × 297	0.03	209 ± 49	...	...	1.22 ± 0.04	2040 ± 680
	20.5	1247 × 931	0.04	≤ 931	...	...	0.26 ± 0.03	>250
2002 Apr 12,13	1.3	91 × 59	0.18	134 ± 9	0.76 ± 0.07	36 ± 10	8.96 ± 0.24	2170 ± 250
	2.0	131 × 98	0.39	166 ± 16	0.63 ± 0.10	41 ± 11	5.32 ± 0.23	2420 ± 450
	3.6	224 × 155	0.03	234 ± 9	0.73 ± 0.05	40 ± 7	2.66 ± 0.04	1690 ± 110
	20.5	1398 × 1146	0.06	≤ 1146	...	...	0.38 ± 0.06	>240
2002 Feb 17,18	1.3	83 × 48	0.14	120 ± 4	0.91 ± 0.04	30 ± 13	10.87 ± 0.17	2750 ± 140
	2.0	128 × 90	0.11	140 ± 13	...	...	5.38 ± 0.22	2150 ± 300
	3.6	200 × 135	0.03	199 ± 8	...	...	2.85 ± 0.04	1830 ± 110
	6.1			...	...	...	...	...
	20.5	1312 × 951	0.05	≤ 951	...	...	0.30 ± 0.05	>270
2001 Jan 02	1.3	78 × 42	0.08	124 ± 2	0.92 ± 0.02	40 ± 8	12.58 ± 0.08	2920 ± 70
2000 Dec 23	0.7	44 × 20	0.18	98 ± 2	0.92 ± 0.02	0 ± 7	29.02 ± 0.30	3070 ± 100

Notes.- The restoring beam and image rms noise values were obtained using uniform weighting and include the Pie Town antenna baselines. The position angles (measured in degrees east of north) of the restoring beams in these images are not given here but are all between 30° and 70°. The major axis of the stellar radio disk, $\theta_{\rm maj}$, the axis ratio of the major and minor radio disks, $\theta_{\rm maj}/\theta_{\rm min}$, the position angle, P.A., and the total flux density, F_ν, are all derived from the best-fit uniform-brightness (T_b) elliptical-disk models.

4.3. *Where are the Hotspots?*

No sign of hotspots (see Harpers pie town proceedings)

5. CONCLUSIONS

The data presented in this paper were obtained with the Karl G. Jansky Very Large Array (VLA) which is an instrument of the National Radio Astronomy Observatory (NRAO). The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. We wish to thank the NRAO helpdesk for their detailed responses to our CASA related queries. This publication has emanated from research conducted with the financial support of Science Foundation Ireland under Grant Number SFI11/RFP.1/AST/3064, and a grant from Trinity College Dublin.

Facilities: VLA.

REFERENCES

Chiosi, C., & Maeder, A. 1986, ARA&A, 24, 329
Danchi, W. C., Bester, M., Degiacomi, C. G., Greenhill, L. J., & Townes, C. H. 1994, AJ, 107, 1469
Harper, G. M., Brown, A., & Guinan, E. F. 2008, AJ, 135, 1430
Josselin, E., & Plez, B. 2007, A&A, 469, 671
Ohnaka, K., et al. 2011, A&A, 529, A163
Smith, M. A., Patten, B. M., & Goldberg, L. 1989, AJ, 98, 2233
Thirumalai, A., & Heyl, J. S. 2012, MNRAS, 422, 1272
van Loon, J. T. 2010, in Astronomical Society of the Pacific Conference Series, Vol. 425, Hot and Cool: Bridging Gaps in Massive Star Evolution, ed. C. Leitherer, P. D. Bennett, P. W. Morris, & J. T. Van Loon, 279

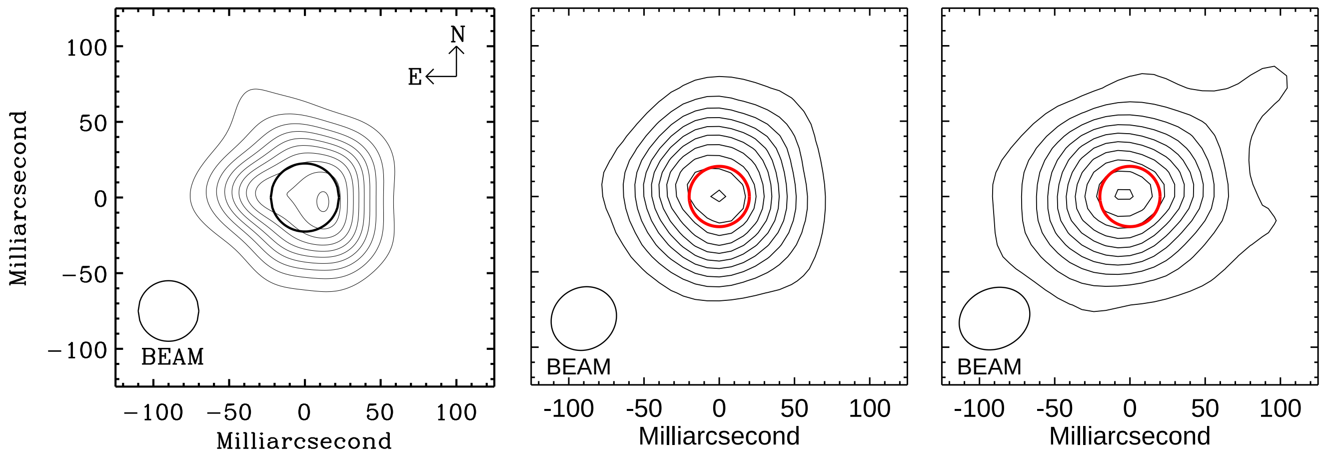

Figure 1. VLA A-configuration maps of Betelgeuse at 0.7 cm.