Radio observations of IRAS selected southern hemisphere classical Be stars

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ABSTRACT
We present the first radio observations of a sample of 13 optically and IR bright southern hemisphere classical Be stars made from the Australian Telescope Compact Array at 3.5cm and 6.3cm simultaneously. One star, $\delta$ Cen was detected at 3.5cm and a second, $\mu$ Cen was also thought to have been detected; further observations of this source are required to confirm this detection. No sources were detected at 6.3cm, although $\delta$ Cen was previously detected at this wavelength by other observers at a higher flux than our detection limit. The radio observations show that the spectral energy distribution undergoes a turnover between the far IR and radio wavelengths, as was seen in previous studies. Likewise we find no simple correlation between far IR and radio flux. Lower limits to the outer disc radius were found to be of the order of few hundred solar radii; of the order of those found previously by Taylor et al.

Key words: Be stars - stars:circumstellar matter - stars:radio emission

1 INTRODUCTION
Classical Be stars are defined as non supergiant B stars that have, or have had Balmer lines in emission. They are further characterised by the presence of a continuum excess, arising from free free and bound free emission from a stellar wind. Comparison of optical and UV spectra show that two different wind regimes must coexist. Consequently a high velocity component responsible for the high excitation lines visible in the UV, and a denser component that produces the near IR continuum excess and the optical emission lines was proposed to explain the observations. That the denser component was concentrated in the equatorial plane has long been suspected; recent interferometric data shows that the envelopes around Be stars are non spherical (Dougherty & Taylor 1992; Quirrenbach et al 1994; Stee et al 1995).

However, only a few of the brightest systems are amenable to an interferometric approach. Consequently, other approaches to the study of Be star circumstellar discs have been attempted. One such approach was long wavelength (mm-radio) flux measurement. When combined with near IR photometry modeling of the spectral energy distribution (SED) leads to a profile of the base density and density gradient (and hence a radial velocity law) within the circumstellar disc. However, observations of Be stars at mm and radio wavelengths showed that they were much fainter than implied by a simple extrapolation of their near IR and IRAS fluxes (e.g. Taylor et al 1990; henceforth Ta90), indicating a change in the ion density gradient within the disc. Several explanations were advanced to explain this, the most favourable being a change in disc opening angle or re-acceleration of material at large radii. Other possibilities exist, such as recombination at large radii or a truncation of the disc; see Waters et al. (1991) and Ta90 for a thorough discussion of all the scenarios.

Given the paucity of detections in the northern hemisphere (only 6 Be stars have been detected), and the lack of multiple observations it is difficult to quantify the behaviour of the continuum excess at long wavelengths. Because of this shortfall we made observations of a sample of 13 bright southern hemisphere Be stars from the Australian Telescope Compact Array (ATCA) in 1997 April/May in an attempt to increase the sample size.

2 OBSERVATIONS
Australian Telescope Compact Array (ATCA) observations were made between 1997 April 30 and 1997 May 4 of a sample of bright Be stars. In order to obtain a data set consistent with observations of northern hemisphere Be stars, the same selection criteria used by Ta90 were adopted (if
an extrapolation of the IRAS fluxes revealed a radio flux of \( \sim 1 \text{mJy} \). This procedure resulted in an inadequate number of stars being selected, the remainder selected on the basis of being within the declination limits of ATCA and being optically/IR bright stars listed in the Bright Star Catalogue. The list of target stars is reproduced in Table 1; it consists of targets at a declination of less than \( \sim 0^\circ \). Quoted IRAS fluxes are those given by Waters et al (1987). We note that BST7342, \( \theta \text{Cir} \) and \( \epsilon \text{Tuc} \) have detections listed in the IRAS point source catalogue, however we only list IRAS fluxes for those stars which satisfy the selection criteria listed in Waters et al (1987). Given the extremely variable nature of the near IR continuum of Be stars (indeed \( \mu \text{Cen} \) is also highly variable in H\( \alpha \)) it is not clear that extrapolation of IRAS data to the present day is valid (either for target selection or data analysis); therefore caution must be applied in the interpretation of such data.

Despite the survey of Ta90 extending to declinations of \( \sim 40^\circ \), only one star \( \alpha \text{Col} \) is included in both surveys. In a second survey of northern Be stars by Apparao (1990; henceforth Ap90) a further two stars, \( \chi \text{Oph} \) and \( \gamma \text{Oph} \) are common to our survey.

The sources were observed with the array in the 1.5A configuration, giving baselines between 153 and 3000 m, simultaneously at 3.5 \& 6.3 cm. This gave a resolution of 4 arcseconds at 6.3cm and 2 arcseconds at 3.5cm. Primary flux calibration was achieved using PKS 1934-638. Observations typically consisted of 20 min on-target interleaved with 5 min on a nearby unresolved phase calibrator. Total observing time on-source was between 1.5-2hrs for each source, over a period of \( \sim 10 \) hrs, giving reasonable \( u-v \) coverage. Data were reduced using the MIRIAD software package. Radio positions and strength of each detection were obtained by fitting 2D gaussians to the radio maps. The typical one sigma rms uncertainty is \( \sim 0.1 \text{mJy} \), 2-3 times more sensitive than previous observations, although some fields were extremely noisy, resulting in larger upper limits to the radio flux (eg the 6.3cm field of \( \pi \text{Aqr} \) which contains a very bright background radio source).

3 RESULTS

We note that out of a sample of 13 stars we obtained only one \( 3\sigma \) detection at 3.5cm; \( \delta \text{Cen} \), which Dougherty et al (1998) confirm \((S_{3.5\text{cm}}=0.67\text{mJy}, S_{6.3\text{cm}}=0.47\text{mJy})\). A detection of an unresolved radio source \( \sim 1.8 \) arcseconds from the optical position of \( \mu \text{Cen} \) was made. With a synthesised beam size of 2.3 \times 1.5 arcseconds this detection is less than a beamsize from the reported optical position; for the purpose of this study we will treat this as a positive detection, although we caution that further observations are required to confirm this. We also note the detection of an unresolved radio source of a magnitude consistent with prior Be star detections \( \sim 4.5^\circ \) south of the optical co-ord of BST7342. We exclude this from further analysis, due to both the distance from the optical source, and also the peculiar nature of BST7342 (thought to be an eclipsing binary component with an A2 supergiant; Jaschek et al. 1990). We therefore detect \( \sim 15 \) per cent of the complete target list, and 25 per cent of the IRAS selected Be stars (including \( \mu \text{Cen} \)), compared to a 30 per cent detection rate by Ta90, and a lack of any detection in the sample of 18 Be stars by Ap90.

None of the sources were detected at 6.3cm; upper limits to the radio flux are presented in Table 1. Surveys of northern hemisphere objects reveal that only two stars, \( \psi \text{Per} \) and \( \beta \text{CMi} \) have been detected at 6cm (Dougherty et al 1991; henceforth D91), with fluxes of 0.23mJy and 0.19mJy respectively. Dougherty et al (1998) report a detection of \( \delta \text{Cen} \) at 6.3cm with a flux of \( 0.47\pm0.07\text{mJy} \), a difference between the two observations of \( \sim 3\sigma \), suggestive (although not conclusive) of variability. We note that the 3.6cm emission arises from a region interior to that of the 6cm emission. Therefore, if the changes in the wind propagate outwards from the stellar surface the 3.6cm emission would also be expected to vary. Of the stars that have been previously observed, \( \alpha \text{Col} \) was not detected by either Ta90 or ourselves; the same is true for the two common targets between this work and Ap90 (\( \chi \text{Oph} \) and 66 \text{Oph}). However, Ap90 failed to detect any of their sample, including the radio bright Be stars \( \gamma \text{Cas} \), \( \psi \text{Per} \), \( \zeta \text{Tau} \) and \( \beta \text{Mon} \).

4 DISCUSSION

Like Ta90 we find no strong correlation between radio and far IR flux (Figure 1). In particular we detect \( \mu \text{Cen} \), despite it having a relatively low IR flux (it is the faintest Be star yet to be detected at radio wavelengths). However given the length of time that has elapsed between the two surveys, it is possible that the far IR flux has varied during this period; \( \mu \text{Cen} \) is known to be optically variable (eg Hauschak et al 1993). If stellar luminosity plays a role in the formation of the circumstellar envelope, one might expect a correlation between radio emission and spectral type. Indeed Ta90 point out that the radio fluxes from later spectral types in their survey are an \( \sim \)order of magnitude lower than those of the earlier spectral type. To enable a com-
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Table 1. Summary of the program stars (distances derived from Hipparcos archival data, spectral types from the Bright Star Catalogue), and observed 3.5cm and 6.3cm fluxes and upper limits (3 sigma) to fluxes. Stars marked with an asterisk were chosen using optical brightness alone, and not from IRAS continuum measurements (see text for selection criteria).

| Star   | Name         | HD   | SP. Type | S[12] (Jy) | S[25] (Jy) | S[60] (Jy) | 3.5cm Flux Density (mJy) | 6.3cm Flux Density (mJy) | Dist. (Pc) | $L_{radio}$ ($10^{16}$ergs$^{-1}$Hz$^{-1}$) |
|--------|--------------|------|----------|------------|------------|------------|------------------------|------------------------|------------|---------------------------------|
| δ Cen  | BS 7342*     | 181615 | B2Vpe+   | <207       | <157       | <146       | <146                   | <146                   | 7.4        | <0.1 |
| α Ara  | BS 7342*     | 181615 | B2Vpe+   | <157       | <146       | <146       | <146                   | <146                   | 1.0        | <0.1 |
| 66 Oph | BS 7342*     | 181615 | B2Vpe+   | <157       | <146       | <146       | <146                   | <146                   | 0.9        | <0.1 |

Table 2. Optical (Hipparcos) and radio positions, and positional offsets of the two possible radio detections (all co-ordinates in J2000).

| Star   | Name         | Detection | Optical | Radio | Offset (arcsec) |
|--------|--------------|-----------|---------|-------|----------------|
| δ Cen  | BS 7342*     | 12 08 21.50 | 50 43 20.7 | 12 08 21.54 | 50 43 20.41 | 0.48 |
| μ Cen  | BS 7342*     | 12 08 21.50 | 50 43 20.7 | 12 08 21.54 | 50 43 20.41 | 1.81 |

Comparison, we have extrapolated the fluxes of our detections to 2cm (see Table 3). We present two values here; firstly a lower limit based on our determination of the spectral index, and a second estimate based on the assumption of a spectral index of $\sim$1.4 (suggested by prior work). In both cases we find that the luminosity is consistent with those measured for the earlier spectral types in Ta90 ($\sim$10$^{16}$-10$^{17}$ erg s$^{-1}$ Hz$^{-1}$), an $\sim$order of magnitude greater than the detections of later spectral types reported in Ta90. We further note that the luminosities of δ Cen and μ Cen differ by 0.5±0.1 10$^{16}$ergs$^{-1}$Hz$^{-1}$ suggesting considerable variance between the circumstellar discs of these two stars (of the same spectral type).

Calculation of the 25μm-3.5cm spectral index are shown in Table 3. For stars for which only upper limits are available we find that the lower limits to the spectral index are of the order $\alpha$=1.2-1.5; indicative of a steepening in the spectral energy distribution between IR and radio wavelengths, as first reported in Taylor et al. (1987). Although two stars (δ Cir and ε Tuc) do not demonstrate this behaviour, we note that they have the steepest IR spectral slopes; therefore we might expect their radio fluxes to lie substantially below the upper limits determined here.

This range of spectral indices confirms the departure of the Be star wind from an isothermal circumstellar disc with a constant disc opening angle and wind velocity with respect to radius, and a constant mass loss rate, for which one would expect to see a spectral index of +0.6 (D91; Wright and Barlow 1975). Therefore, as concluded in previous work one or more of these underlying assumptions must be incorrect. Under the assumption of a constant opening angle and an isothermal disc it is possible to relate the spectral index to the density gradient (and hence radial velocity gradient) within the circumstellar disc (D91). For a radial density law of the form $\rho \propto r^{-\beta}$ we find that the spectral index, $\alpha$, is related to $\beta$ by (Wright and Barlow 1975)

$$\beta = (6.2 - \alpha)/(4 - 2\alpha)$$ (1)

The lower limits to the density gradient implied by the spectral indices are listed in Table 3. Waters et al (1987) show that for the majority of Be stars, the value of $\beta$ determined from IRAS measurements is consistently between 2-3. Values of $\beta$ in excess of 2 are of interest as they imply either an acceleration of disc material or a non constant disc opening angle (Ta90). Of the stars detected here, the lower limit for μ Cen is consistent with these values, while that of δ Cen exceeds it. Near IR observations of the Be star X Persei also indicate a high value for $\beta$ (Telting et al 1997). The symmetric Hα profile argue against an explanation for this value in terms of a large density/velocity gradient alone, which would lead to a very asymmetric profile. Since it is expected that the radio continuum will be formed at larger radii than Hα emission, it is possible that the large values of $\beta$ do represent a real velocity gradient (ie an acceleration) at large radii within the disc, as is suggested by Ta87, and not just a departure from the isothermal assumption as suggested by Telting et al (1997). However, the 3.5cm and 6.3cm detections of δ Cen by Dougherty et al (1998) are suggestive of a possible change in the spectral index (to a value close to the canonical value for an isothermal, constant velocity wind; $\alpha \sim 0.6$). A change in the spectral index in two stars is also reported in D91; it therefore seems likely that changes in the global structure of the circumstellar envelope and/or velocity profile are possible. At present it is impossible to determine if this is a result of changes in the disc geometry.
Table 3. Spectral index, minimum radial density gradient, and minimum outer disc radius for the 2 radio detections. Also listed are the extrapolated 2cm fluxes based on the observed lower limits to the spectral index, and also the canonical value of $\alpha=1.4$ (units of $10^{37}\text{ergs}^{-1}\text{Hz}^{-1}$).

| Object | IR-Radio Spectral Index | Radio Spectral Index($\alpha$) | Density Gradient ($\beta$) | Minimum Disc Radius ($R_\odot$) | Extrapolated 2cm Flux |
|--------|-------------------------|-------------------------------|---------------------------|---------------------------------|-----------------------|
| $\delta$ Cen | 1.29±0.02 | >1.18 | >3.1 | 421 | >2.1 | 2.4±0.1 |
| $\mu$ Cen | 1.11±0.03 | >0.87 | >2.4 | 326 | >1.0 | 1.3±0.2 |

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5 CONCLUSIONS

As a result of observations of a sample of 13 IR bright southern Be stars we have identified $\delta$ Cen as a radio source, which may also be variable. A second star, $\mu$ Cen, is also thought to be a radio emitter, although further observations are needed to confirm this. This brings the total number of Be stars detected at radio wavelengths to eight (inclusive of $\mu$ Cen). We confirm earlier results of Ta90 that demonstrate a turnover in the spectral energy distribution between the far IR and radio wavelengths. We find no compelling evidence for a direct correlation between stellar or far IR luminosity and radio flux. Clearly further observations of Be stars at higher sensitivities are required before such a correlation can be confirmed or rejected. Measurement of the minimum outer disc radius reveals that the circumstellar discs extend to several hundred solar radii, again reproducing the results of Ta90.

or velocity structure (ie absence of an accelerating force at large radii during this time). Under the assumption of an optically thick disc, we can derive estimates for the minimum outer disc radius of the Be stars. Using the method detailed in Ta90 we obtained estimates of the minimum radius for an optically thick spherical wind to produce the observed fluxes. Since Be star winds are thought to be both partially optically thin, and also disc like, this estimate will also serve as a lower estimate to the outer disc radius (see Table 3). The values obtained, of the same order as those derived in Ta90 clearly show the disc can extend to large distances from the star in some systems. In contrast to these values Coté et al (1996) analyse the near IR SED of the Be stars BS7739 and $\eta$ Cen and find that to explain the steep spectrum the discs must undergo a steepening in density gradient at only a few-10R*.. Observations of 4 Herculis (Koubsky et al. 1997) also show that during the onset of an episode of Be activity a pseudo photosphere of material was formed in the equatorial regions of the star, which gradually formed an extended envelope around the star. Therefore, it would appear that Be star disc size and structure can vary widely between individual stars. Whether such extremes represent stable configurations, or are a result of viewing discs in varying stages of their evolution is as yet unknown.