Wide-field imaging and polarimetry for the biggest and brightest in the 20-GHz southern sky

S. Burke-Spolaor,1,2,3⋆ R. D. Ekers,2 M. Massardi,2,4 T. Murphy,5,6 B. Partridge,1 R. Ricci2,7 and E. M. Sadler5

1Haverford College Astronomy Department, 370 Lancaster Avenue, Haverford, PA 19041, USA
2Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 1710, Australia
3Swinburne University of Technology Centre for Astrophysics and Supercomputing, Hawthorn, VIC 3122, Australia
4SISSA/ISAS, Via Beirut 2-4, I-34014 Trieste, Italy
5Sydney Institute for Astronomy, The University of Sydney, NSW 2006, Australia
6School of Information Technologies, The University of Sydney, NSW 2006, Australia
7Department of Physics and Astronomy, University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4, Canada

Accepted 2009 January 24. Received 2009 January 23; in original form 2008 December 5

ABSTRACT

We present the wide-field imaging and polarimetry at \( \nu = 20 \text{GHz} \) of seven most extended, bright \((S_{\text{total}} \geq 0.50 \text{Jy})\), high-frequency selected radio sources in the southern sky with declinations \( \delta < -30^\circ \). Accompanying the data are brief reviews of the literature for each source. The results presented here aid in the statistical completeness of the Australia Telescope 20-GHz Survey: the Bright Source Sample. The data are of crucial interest for future cosmic microwave background missions as a collection of information about candidate calibrator sources. We were able to obtain data for seven of the nine sources identified by our selection criteria. We report that Pictor A is thus far the best extragalactic calibrator candidate for the Low Frequency Instrument of the Planck European Space Agency mission due to its high level of integrated polarized flux density \((\sim 0.50 \pm 0.06 \text{Jy})\) on a scale of 10 arcmin. Six out of the seven sources have a clearly detected compact radio core in our images, with either a null detection or less than 2 per cent detection of polarized emission from the nuclei. Most sources with detected jets have magnetic field alignments running in a longitudinal configuration, however, PKS 1333−33 exhibits transverse fields and an orthogonal change in field geometry from nucleus to jets.

Key words: polarization – galaxies: active – galaxies: magnetic fields – cosmic microwave background – radio continuum: galaxies.

1 INTRODUCTION

The Australia Telescope 20-GHz (AT20G) Survey is a blind 20-GHz survey of the whole southern sky (Ricci et al. 2004). The project outlined in this paper complements two subprojects of the AT20G Survey: the first is the AT20G Bright Source Sample (BSS; Massardi et al. 2008), and the second a high-sensitivity polarization study of a subset of the BSS (Burke-Spolaor et al., in preparation). The collective goal of these sister projects was to analyse the total intensity and polarization statistical properties for a flux density limited sample of sources selected at 20 GHz. The BSS used sources south of \( \delta = -15^\circ \), while the Burke sample focused on sources south of \( \delta = -30^\circ \). Both samples included all extragalactic AT20G objects which were brighter than 0.50 Jy, and are primarily composed of a population of compact objects, with 85 per cent showing a flat spectrum \((\alpha > -0.5; S_\nu \propto \nu^{\alpha})\) at high radio frequency (Massardi et al. 2008).

This paper enhances the two projects by providing flux density and polarization data for objects of angular extent beyond approximately 2.4 arcmin, for which accurate data could not be obtained using a single interferometric synthesis field. This paper includes sources only south of \( \delta = -30^\circ \).

Information about nearby, bright sources is of importance to observations of the cosmic microwave background (CMB), in particular the current focus on detecting anisotropies in the polarized CMB signature. Thompson scattering on the last scattering surface produces linear polarization and curl-free patterns termed ‘E-modes,’ which on small angular scales provide information about structures in the early Universe. Observations of compact CMB foreground sources are necessary to distinguish between real E-modes and signal scattered by gravitational lensing of the CMB on point source angular scales. Additionally, the diffuse plasmas in bright, extended extragalactic sources can form patterns which are termed ‘B-mode’

⋆E-mail: sburke@astro.swin.edu.au
polarization (Hu, Hedman & Zaldarriaga 2003); B-mode signal in the radio lobes of extragalactic sources may be unsurprising and can be caused by complex magnetic fields in the sources and irregular substructures of different Faraday rotation. However, the positive detection of a similar B-mode polarization signal in the CMB is a major goal of increasingly sensitive measurements of CMB anisotropy. A B-mode signal in the CMB is predicted to occur only by CMB models with tensor (gravitational wave) fluctuations; these are in turn tied to the rapid period of expansion that may have occurred prior to the recombination epoch. The detection of B-mode CMB anisotropies will give insight into the energy scales that occurred directly prior to inflation and would suggest the presence of gravitational waves. However, the amplitude of the cosmological B-mode signals is extremely small, and will require careful attention to foreground signals that might mimic it. On small angular scales where extended and complex foreground sources (such as radio galaxies) are resolved, removing contamination due to extragalactic sources becomes particularly important. For faint, confused and unresolved extragalactic sources in CMB data, a statistical correction may become necessary to calibrate and interpret the results of a cosmic background B-mode analysis.

Bright, highly polarized sources are also necessary for upcoming CMB instruments, in particular, the ESA Planck satellite mission’s Low Frequency Instrument (LFI), which will observe in bands between 30 and 70 GHz (Bersanelli & Mandolesi 2000). Among the source types that have been pursued as potential flux density and polarization calibrators for the instrument are extragalactic sources; however, as the spectral behaviour of the bright extragalactic population at high frequency is difficult to model, sources selected at lower frequency are not certain to be suitable calibrator candidates. With our observations, along with the catalogues of Massardi et al. (2008) and Burke et al. (in preparation), we provide a list and homogeneous observations of bright and strongly polarized sources that are selected at a frequency closer to CMB observing frequencies than was previously available.

In Section 2 we outline the criteria used in the selection of our sources and summarize the literature accompanying each source. Section 3 details the data collection, calibration and wide-field imaging process used to create our results. Finally, the data (full intensity and polarization vector images and values) are presented in Section 4 with a discussion about the images, high-frequency polarimetry and the implications of our results. Section 5 provides a brief summary of our findings.

2 SOURCE SELECTION AND LITERATURE REVIEW

The AT20G team’s confirmation follow-up observations to their initial transit scan survey provided a list of sources detected at 20 GHz, from which Burke et al. (in preparation) selected a sample of sources at declinations $-30^\circ < \delta < -70^\circ$ whose total intensity exceeded 0.50 Jy. Preliminary results of an AT20G pilot survey are available in Sadler et al. (2006); a description of the blind scan and follow-up observations of the AT20G survey are available in Massardi et al. (2008). The 2.4-arcmin primary beam full width at half-maximum (FWHM) and the 80 to 200 m interferometer spacings used in the AT20G follow-up did not provide accurate flux density measurements for the most extended sources, and furthermore left cases in which sources were either (1) fully resolved (and therefore undetected) by the 60 m shortest antenna spacing of the AT20G follow-up, or (2) had compact components (hotspots, cores) which were detected as separate, $\leq 0.50$ Jy sources in the follow-up. The Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003) and the Parkes-MIT-NRAO (PMN) Southern (Condon, Griffith & Wright 1993; Wright et al. 1994) and Zenith Surveys (Wright et al. 1996) have a higher sensitivity to extended radio sources. This is due to their more complete Fourier coverage for short baselines, and due to the lower observing frequency of the two surveys which allowed higher sensitivity to diffuse, steeper spectrum radio components (SUMSS at 0.843 GHz, PMN at 5 GHz).

To recover highly resolved 20-GHz sources, we cross-referenced multiple-component AT20G sources against SUMSS images. This indicated AT20G sources which appeared to be compact components of one larger, extended object. We then ran a search for sources which are highly extended and thus may have been completely resolved out by the AT20G observations. We expect any extended source with $S_{20} > 0.5$ Jy to have a 5-GHz flux of $S_5 > 0.9$ Jy if it has a spectral index of less than $-0.5$, as would be expected by a conservative estimate for the spectral index of diffuse emission. We thus compiled a list of the sources in the PMN catalogue which are flagged as extended and have an integrated 5-GHz intensity greater than 900 mJy. By including these objects and those selected at 20 GHz, this sample has a nominal flux limit for extended sources with $S_{20} > 0.50$ Jy. However, due to the spatial resolution limit of PMN and our decision to include only sources flagged as extended in PMN, the sample is not complete for sources of scales between 2.4 and 4.2 arcmin. The number of missing sources in this range is estimated to be between four and 10 based on source count extrapolations.

Sources which were associated with the Large and Small Magellanic Clouds (LMC, SMC) or in the Galactic plane ($|b| < 1.5$) were excluded from the sample, as were supernova remnants with $|b| > 1.5$.

In summation, a source was included if it

(i) is in the region $-30^\circ < \delta < -70^\circ$;

(ii) is extragalactic (not including LMC, SMC);

(iii) was detected as a multiple-component (hotspots/core) source within the AT20G follow-up beam with a total flux of $S_{\text{tot}} > 0.50$ Jy;

or

(iv) is marked in PMN as extended, with $S_5 > 0.90$ Jy.

If a source obeyed all the above criteria, it was included in our sample.

The resulting list from the searching process consisted of nine objects. However, we did not observe Fornax A due to its highly diffuse emission, most of which would remain undetected even in ATCA’s most compact configuration (furthermore, attempts to detect the nucleus of the galaxy at 20 GHz during unscheduled ATCA telescope time were unsuccessful down to a few milliJansky). For some sources, only subregions containing compact structure were observed. The full nine sources detected by our criteria are listed in Table 1, which provides information on what part of the source was observed (if applicable). Below, the radio morphology of each source is described, and significant literature and interesting properties for each object are summarized. 

PKS0131–36 (NGC612), Fig. 1. An asymmetric, Faranoff-Reilly II source with a bright knot in one jet at low radio frequency (Mauch et al. 2003). Associated at optical wavelengths with a magnitude 15 S0-type galaxy (Bolton, Gardener & Mackey 1964). Westerlund & Smith (1966) note a radio–optical morphology similar to Centaurus A, with a dust lane crossing the core and an asymmetric positioning of the core along the axis of the two radio lobes.
Recently, a study of H\textsc{i} gas in the galaxy demonstrated the existence of a huge, 140-kpc disc along NGC 612’s dust lane and a faint bridge of H\textsc{i} emission to the nearby galaxy NGC 619, indicating a possibly recent or ongoing interaction in this system (Emonts et al. 2008). The source resides near the centre of a cluster of galaxies (Schilizzi 1975). Redshift measured by Ekers et al. (1978).

**Fornax A (NGC 1316).** Fornax A is a highly diffuse, symmetrical double-lobed galaxy extending approximately 1° along its major axis. Source is associated with the peculiar S0 galaxy NGC 1316 (Mills 1954; Ferguson 1989). The source resides in the Fornax cluster. The high-resolution observations of Goldzahler & Fomalont (1984) across 1.5, 4.9 and 15.0 GHz indicate a steep-spectrum core and non-linear jets. The large-scale structure of the radio source was studied by Ekers et al. (1983), who noted a bridge of emission extending between the lobes that is displaced from NGC 1316’s centre; this morphological feature and the complicated dynamics of the galaxy lead to their description of a formation scenario involving multiple galaxy collisions. Caon, Capaccioli & D’Onofrio (1994) further suggest Fornax A’s host as a merger remnant, noting tidal tails, filaments, dust lanes and a low velocity dispersion. Although too diffuse to make useful measurements with our telescope configuration, the source was detected in *Wilkinson Microwave Anisotropy Probe* (WMAP) at 23 GHz with a flux of $S_{23} = 11.7 \pm 0.1$ (Bennett et al. 2003). The redshift given in the table is as measured by Longhetti et al. (1998).

**Pictor A, Fig. 2.** A classic double radio galaxy with significant hotspots, identified both as a D-type galaxy (Schilizzi 1975) and as an N-type galaxy with strong X-ray emission by Marshall et al. (1978). It is known to be hosted by a smooth, $e \sim 0.7$ elliptical galaxy with a sharp nucleus and little to no filamentary structure (Danziger, Fosbury & Penston 1977). Extensive observations and analysis have been done of this source. These include studies of its rotation measure, for instance Berge & Seielstad (1967) and Haves (1975) give $RM = 46 \pm 1$, $\theta_0 = 104 \pm 4$ and $RM = 51 \pm 4$, $\theta_0 = 100 \pm 6$, respectively, where $\theta_0$ is the calculated zero-wavelength polarization angle. In addition, there have been high-resolution observations (Preuss & Fosbury 1983 note a radio nucleus of parsec scale) and central black hole mass estimations (Lewis & Eracleous 2006 estimate $M_{BH} = 4 \pm 2 \times 10^7 M_\odot$ using stellar velocity dispersion). The western radio lobe contains a bright hotspot that shows highly polarized (optical polarization degree $\sim 55$ per cent) optical synchrotron emission and coincident X-ray signal from which Roeser & Meisenheimer (1987) conclude pure synchrotron emission from radio to X-ray wavelengths. A deep optical study of the western hotspot by Thomson, Crane & Mackay (1995) confirm this conclusion. The study also notes strong polarization of the hotspot with a magnetic field oriented perpendicularly to the jet axis. A thorough X-ray study of Pictor A was done by Wilson, Young & Shopbell (2001), noting significant emission in the core, bright western hotspot, and along a jet extending from the core to the hotspot. High quality imaging of Pictor A is available at various wavelengths (e.g. Perley, Roeser & Meisenheimer 1997; Malkan, Gorjian & Tan 1998; Simkin et al. 1999; Tingay et al. 2000). Redshift measured by Schmidt (1965).

**Centaurus A (NGC 5128),** Fig. 3. A very complex and highly extended radio source associated with a spherical galaxy crossed by large, absorptive dust lanes. Being the nearest and one of the first radio galaxies identified, the literature is incredibly extensive and too vast to summarize here. A seminal study of the large-scale radio structure of the source from 500 MHz to 5 GHz was made by Cooper, Price & Cole (1965); the optical identification was made by Bolton, Stanley & Slee (1949). The redshift measurement is available from Graham (1978).

**PKS 1333–33 (IC 4296),** Fig. 4. A ‘triple’ radio source called thus for its bright inner jets and diffuse outer lobes that are in alignment along the jet axes. The major lobes extend approximately 30 arcmin and the inner lobes are within 2 arcmin of the centroid (Goss et al. 1977; Jones & McAdam 1992). The radio source is associated with the E1 galaxy IC 4296, which is a companion to IC 4299 and is centrally located in the galaxy cluster Abell 3565 (Huchra & Geller 1982; Yunis, Meaburn & Stewart 1985). The host galaxy is claimed to have a dusty disc by Colbert, Mulchaey & Zabludoff (2001) and Schmitt et al. (2002); however, Sadler & Gerhard (1985) and Michard (1998) saw no significant dust features. Killeen, Bicknell & Ekers (1986a) and Killeen, Bicknell & Carter (1986b) provide thorough multiwavelength studies of the radio polarization and rotation measures, and studies of the optical, infrared and X-ray form of the source with an extensive analysis presented in Killeen & Bicknell (1988). The redshift was most recently measured by Smith et al. (2000).
20-GHz extragalactic imaging and polarimetry

Figure 1. PKS 0131−36. The beam shape is indicated in the lower right-hand corner of the images in panels (a) and (b). (a) Radio reference map and grey-scale image of total intensity. An ‘X’ indicates the position of the associated optical galaxy. The reference radio map was constructed using an 843-MHz image from the SUMSS postage stamp server, available at http://www.astrophysics.usyd.edu.au/SUMSS, while the grey-scale image was created from our 18-GHz mosaic data. The radio reference map highlights the FWHM of the ATCA primary beam for the mosaic fields; note that the apparent termination of the source at the edges of the observation field is due only to decreased sensitivity near the edge of our field of view. (b) 18-GHz polarization map. Vectors show the observed degree and orientation of the electric field vectors, while contours trace the total intensity of the radio source at levels given in the text below the image. The rod in the lower right-hand corner of the image indicates the length of a 100 per cent polarized component.

Centaurus B, Fig. 5. This is a double-lobed source spanning approximately 15 arcmin, identified with a large, red E0 galaxy by Laustsen, Schuster & West (1977). The galaxy is close to the Galactic plane ($b \sim 1.73$), and as noted by Jones, Lloyd & McAdam (2001), literature flux estimates are often confused by Galactic foregrounds. However, Jones et al. (2001) present a comprehensive multifrequency study of the radio galaxy, finding a close power-law fit to the spectrum with a spectral index of $\sim -0.73$. Extrapolating their published measurements, we predict an integrated 20-GHz flux value of $S_{20} \sim 14.6$ Jy. The redshift quoted in the table was measured by West & Tarenghi (1989).

PKS 1610−60, Fig. 6. The radio source is a wide-angle head–tail galaxy with bright inner lobes and diffuse tails [mapped by Schilizzi & McAdam (1975), Jones & McAdam (1992), Christiansen et al. (1977) and Gregory et al. (1994) at 408, 843, 1415 and 4850 MHz, respectively]. Ekers (1970) identified the source with an E3 galaxy at $J2000 \alpha = 16:15:1.7, \delta = -60:55:13.7$. The galaxy is thought (but not yet proved) to be a central member of the local massive cluster Abell 3627 (Robertson & Roach 1990; Brown & Burns 1991; Boehringer et al. 1996). Another head–tail galaxy lies within 1° of PKS 1610−60; Jones & McAdam (1996) mapped the two sources at 1360 MHz, explaining PKS 1610−60’s morphology (sharp kinks
in the jets and the wide tail separation) through probable interaction with an intercluster medium and influence from subcluster mergers. Most recently, a redshift was determined by Woudt et al. (2004).

**PKS 2153−69**, Fig. 7. Less than 3 arcmin in extent, the radio structure of this Seyfert 2 galaxy consists of a core-lobe morphology. A presumably unrelated source lies approximately 2.5 arcmin to the east (Ekers 1969; Christiansen et al. 1977). The host galaxy is an early type of class E0 (Schilizzi 1975; Marenbach & Appenzeller 1982), and has been shown to have an extranuclear ionized gas cloud with which the jets are interacting (Tadhunter et al. 1988; Tingay et al. 1996). Further deep radio and X-ray studies have been performed by Fosbury et al. (1998) and Young et al. (2005). The galaxy was modelled to have a long-period (\( t \sim 1.8 \times 10^6 \) yr) jet precession by Lu & Zhou (2005). Redshift given by Da Costa et al. (1991).

**PKS 2356−61**, Fig. 8. A Faranoff–Riley II galaxy marked by four bright regions of emission that are slightly asymmetric about a core. In addition, there is a diffuse arm of emission extending south-west from the western inner lobe (see e.g. low radio frequency images\(^1\) by Christiansen et al. 1977; Jones & McAdam 1992; Subrahmanyan, Saripalli & Hunstead 1996; Burgess & Hunstead 2006). Identified

\(^1\) An unpublished image of this source is available from the Australia Telescope National Facility (ATNF) at http://www.narrabri.atnf.csiro.au/public/images/pks2356-61
20-GHz extragalactic imaging and polarimetry

Figure 3. Centaurus A. The beam shape is indicated in the lower left-hand corner of the images in panels (a) and (b). (a) Radio reference map and 18-GHz grey-scale image of total intensity. An ‘X’ indicates the position of the associated optical galaxy. The 5.0-GHz reference radio map was reproduced from Junkes et al. (1993). The radio reference map highlights the FWHM of the primary beam for our mosaic fields. (b) 18-GHz polarization map. Vectors show the observed degree and orientation of the electric field vectors, while contours trace the total intensity of the radio source at levels given in the text below the image. The rod in the lower left-hand corner of the image indicates the length of a 100 per cent polarized component.

with an E3 galaxy by Whiteoak (1972) and Schilizzi (1975). Suspected to be a member of galaxy cluster SC 2357–61 (Westerlund & Smith 1966; Teague, Carter & Gray 1990). Source was detected as a hard X-ray emitter by Landi, Malizia & Bassani (2005). Redshift measured by Loveday et al. (1996).

3 OBSERVATIONS AND DATA REDUCTION
All sources were observed with the Australia Telescope Compact Array (ATCA). The compact configuration H75 has five 22-m dishes extending on perpendicular north–south and east–west arms with
Figure 4. PKS 1333–33. The beam shape is indicated in the lower right-hand corner of the images in panels (a) and (b). (a) 843-MHz radio reference map reproduced from Jones & McAdam (1992) with permission from Bruce McAdam, and 18-GHz grey-scale image of total intensity. The radio reference map highlights the FWHM of the primary beam for our mosaic fields. An ‘X’ indicates the position of the associated optical galaxy. (b) 18-GHz polarization map. Vectors show the observed degree and orientation of the electric field vectors, while contours trace the total intensity of the radio source at levels given in the text below the image. The rod in the lower right-hand corner of the image indicates the length of a 100 per cent polarized component.

The dish size and maximum baseline correspond to a field of view of 2.6 arcmin and a resolution of 43 arcsec at our mean observing frequency of 18.0 GHz. Because all the sources extended beyond the primary beam size of the telescope, each source was observed using ATCA’s ‘mosaic mode’; the mosaicking technique is commonly used for wide-field imaging at the ATCA. Overlapping, adjacent telescope pointings that were later jointly deconvolved as

a maximum baseline of approximately 80 m. The array was well suited to obtain sufficient (\(u, v\)) coverage to sample and image large, diffuse structures at high radio frequencies over a short period of time. Each source was observed simultaneously at 16.7 and 19.4 GHz in two polarizations using linear feeds with 128 MHz bandwidth at each frequency. Observations took place on 2006 October 1.

© 2009 The Authors. Journal compilation © 2009 RAS, MNRAS 395, 504–517
one observation were taken in a hexagonal pattern with field centres spaced at approximately 1.5 arcmin. The field spacings, given by the Nyquist sampling limit for a hexagonal grid,

$$\theta = \frac{\lambda}{3D}$$

(1)

where $\theta$ is the angular size of pointing separation and $D$ is the primary beam FWHM) ensure a constant noise level across overlapping regions of observation. Additionally, the joint processing of the hexagonally interleaved telescope pointings give the interferometer a sensitivity to large scale emission that is comparable to single-dish (zero-spacing) scales. Each mosaic subfield was observed for 40 s, and a secondary calibrator was observed before and after each mosaiced source. Calibrator and mosaic sets were performed four times for each source at a range of hour angles.

All data were calibrated using the MIRIAD software package (Sault, Teuben & Wright 1993). Throughout calibration the two IF bands were treated independently. After opacity corrections and $xy$ feed phase difference solutions were applied, the bandpass was calibrated using a standard bandpass calibrator (PKS B1921−293), and a primary flux density scaling was solved for using a standard ATCA primary flux calibrator, PKS B1934−638. These calibrators were both observed once only, directly prior to the observing run. Each secondary calibrator was used to simultaneously solve for antenna gain matrices, the residual $xy$-phase difference, and polarization leakage terms (which result from slight imperfections in feed alignment). Solutions from this process were then applied to each subfield. In the case of Centaurus A, additional self-calibration with a single Gaussian component model was needed for fields containing the bright core of the source.

Because of current limitations and software incompatibility in some of the deconvolution algorithms, our measurement of total polarized flux and the images published in this work show the results of MIRIAD’s joint deconvolution polarization maximum entropy method algorithm (PMOSMEM), while the total intensity measurements are extracted from a new multiscale clean deconvolution algorithm implemented in the Common Astronomical Software Applications (CASA) software package (McMullin et al. 2007; Cornwell 2008). In MIRIAD’s joint deconvolution scheme, all subfields are inverted as one image, and the dirty Stokes $Q$ and $U$ maps are set to the same gridding as the total intensity image. The algorithm performs a maximum entropy method deconvolution simultaneously for all polarizations, using morphological information from bright emission in the total intensity image to solve for the $Q$ and $U$ polarized Stokes images. Images are then restored using a Gaussian with the same half-power beamwidth of the synthesized beam. While this method does produce a morphologically correct total intensity image, the MEM algorithm is not optimum for computing total intensities, causing integrated intensity measurements to be systematically high by about 1 to 20 per cent. For this reason, we used CASA’s multiscale clean (again joining mosaic subfields) to deconvolve images and gather intensity information. While CASA does compute polarization values, a known error in the data interface for ATCA polarization information currently renders their output erroneous.

Polarization images were created by combining aligned $Q$ and $U$ images pixel-by-pixel, calculating total polarized intensity, $P$, using $P = \sqrt{Q^2 + U^2}$. A noise term, $\sigma_P$, was estimated from the rms of the region of the Stokes $Q$ image that did not contain source emission. Polarized signal below $3\sigma_P$ was considered undetected and was masked from the polarized intensity map. The masked polarized maps were then corrected for a debiasing factor, using a first-order correction that again uses $\sigma_P$: $P_{\text{final}} = \sqrt{P^2 - \sigma_P^2}$.

Position angle (PA) maps are also calculated on a per pixel basis, with $\psi = (1/2)\arctan(U/Q)$, where $\psi$ is the observed angle of polarization. Vector maps of fractional polarized intensity were formed by dividing the masked total polarization maps by the total intensity maps; in this way, the maps will only show fractional polarization above the detection threshold. Polarization vectors were then calculated using lengths determined by fractional polarization levels, and PAs from PA maps. Note that the orientation of a polarization ‘vector’ is ambiguous by 180°, and does not provide a preferred electric or magnetic field direction along the printed rods.

4 IMAGES AND DISCUSSION

4.1 Results and image description

Table 2 gives various observed and calculated parameters from the data. The columns are as follows: (1) source name; sources with a detected nucleus have a core position fitted with a point source model, which also provides a measurement for the flux density of

2 See http://www.atnf.csiro.au/computing/software/miriad for further details of mosaic observations.

3 The debiasing term is necessary to correct the Ricean bias that occurs from the calculation of $P$ from $Q$ and $U$ terms; there are multiple methods of correction as detailed in Leahy & Fernini (1989).
Figure 5. continued.
Figure 6. PKS 1610–60. The beam shape is indicated in the lower left-hand corner of the images in panels (a) and (b). (a) The 18-GHz grey-scale image of total intensity. An ‘X’ indicates the position of the associated optical galaxy. (b) 18-GHz polarization map. Vectors show the observed degree and orientation of the electric field vectors, while contours trace the total intensity of the radio source at levels given in the text below the image. The rod in the lower left-hand corner of the image indicates the length of a 100 per cent polarized component.
4.2 General properties at 20 GHz

There are several striking and perhaps expected similarities between all the sources. Six of the objects (apart from PKS 2153−69) have clearly detected emission from their nuclei, which in some cases were not easily visible in lower frequency images; all cores have either undetected or very low values of polarization (an upper limit on the polarization of the cores can be calculated by taking 3σp from Table 2). The undetected polarization of the cores could be the result of several different effects. The low values of polarization can be explained by a complex scattering medium surrounding the inner regions of jet formation, or by a dense plasma. Furthermore, this supposition is the high (∼1000 rad m⁻²) rotation measures noted in the inner regions of some active galactic nuclei (AGN). However, studies of galactic nuclei have been yet unable to characterize the spectral properties for emission from AGN; the complex spectra are unable to be fit by pure synchrotron self-absorption or free-free spectra. An equally likely case is the beam depolarization of...
close, compact regions of structure that we have not resolved due to our lower angular resolution. With milliarcsecond resolution, the pilot VLBA Imaging Polarimetry Survey (VIPS; Taylor et al. 2005) has demonstrated that a sample of 24 AGN average below ~3 per cent polarization at 15 GHz, however, the full VIPS sample will provide a more numerically significant assessment for high-resolution polarization.

In several of the sources (especially in the lobes of Pictor A, Centaurus A and the inner hotspots of PKS 1610−60), a notable edge-brightening effect in fractional polarization is visible. While this is a feature common to many extended extragalactic sources, it appears in only a few of the sources here. The interpretation given by Perley et al. (1997) for this effect and of the perpendicularity of polarization alignment to isocontours of total flux density in the western hotspot in Pictor A calls upon the change in field geometry across the lobe. This interpretation can be supported by the absence of these effects in the geometry and strength of observed polarization in the linear jet regions in several of the sources here (for instance, the narrow regions of PKS 1610−60 at α ~ 16:15:27 and ~16:14:35−50, and of PKS 2356−61 at α ~ 23:59:17 and ~23:58:53). In these cases, if there is insignificant or no rotation of polarized signal, the magnetic field along the jets appears to be aligned with the jet axis, and across the entire region there is no apparent change in geometry, nor any apparent limb brightening in polarization.

### 4.3 Individual properties at 20 GHz

The inner jets of PKS 1333−33 are unique for this sample in their alignment; the perpendicular change in magnetic field orientation witnessed in transition from the core to the jets agrees with that observed by Killeen et al. (1986a). The reason for this transition is unclear, though could be explained through relativistic shock interactions with a medium surrounding the nucleus. Transverse orientations of magnetic fields are often observed in BL Lacertae objects, for instance in the VLBI observations of Gabuzda, Pushkarev & Cawthorne (2000).

Centaurus B in addition shows a striking alignment fidelity in the outer regions of the source, with magnetic fields running perpendicular to the jet axis along the brighter areas of the lobes. There is a sharp change in direction and a brightening at the edge of the lobes, and the core is polarized at approximately 90° to the jet emission.

In a qualitative way, we can compare the observed electric field vectors in our images with the lower frequency images of polarized structure published in previous papers that have been corrected for rotation measure. Often images are published of magnetic field orientation, in which case vector images will show vectors perpendicular to the electric field lines. In the case of Pictor A, the 5-GHz images of Perley et al. (1997), which have been corrected for a rotation measure of 45 rad m$^{-2}$ (which corresponds to a rotation at 18 GHz of 0.7) are in good alignment with our uncorrected images, where polarization has been detected by both observations across all regions of the source. The detailed 20-cm images published by Killeen et al. (1986a) of the inner lobes of PKS 1333−33 show rotation-corrected magnetic fields in the lobes that are perpendicular to the jet axis. This is again in agreement with the results of our polarimetry, which show electric field vectors running directly parallel to the jet axis. To quantify the relative changes in spectral index and polarization for different source components in each source, a more rigorous wide field multifrequency observing campaign will be necessary.

### 4.4 Prospects for CMB mission calibration

Beam depolarization imposes a restriction on sources as suitable CMB mission polarimeter candidates. The requirements for a good flux density and polarization calibrator for the lower end of Planck’s observing frequencies (the lowest band centre on the LFI is 30 GHz) include integrated emission >1 Jy across the observation bands, polarized intensity at levels >200 mJy and unresolved emission within the telescope beam. The LFI beam resolutions range from ~33 arcmin at 30 GHz to 14 arcmin at 70 GHz (The Planck Consortium 2005). The flight path and pointing path of the Planck satellite are such that the north and south ecliptic poles will be observed often, such that a source in the region around the south ecliptic pole would be in an ideal position. A limitation on source size coupled with the depolarization that will certainly occur within the large Planck beams means that the brightly polarized northern inner lobe of Centaurus A, for example, cannot be easily isolated and used for calibration.

The best candidate to arise from this data set is Pictor A, which fits the Planck requirements in several ways. In total, the source extends approximately 10 arcmin; the source yields ~0.5 Jy of integrated polarized intensity, which is dominated by the brightly polarized western hotspot. Because the emission from the hotspot is highly diffuse and many light years in linear size, total and polarized emission from this region cannot change rapidly with time, making the source particularly useful for the long observing term of the Planck.
mission and more useful than highly polarized sources which are more compact, variable sources. Conveniently, Pictor A is located within 20° of the south ecliptic pole. The usability of Pictor A as a high-frequency calibrator is limited by its angular size, which may be marginally resolved at the highest frequency, and its spectral index, which is in decline at $\nu > 20$ GHz; both of these could limit the use of Pictor A as a flux density calibrator at the upper ends of the LFI bands. The integrated spectrum of Pictor A is plotted in Fig. 9. Overplotted is the log-linear spectral fit of Perley et al. (1997), which was fit to data below 5 GHz; the higher frequency WMAP data and the data from our observations generally follow this log-linear trend, implying that this spectral index will continue into the relevant Planck bands. Currently, Pictor A stands as the best candidate from all known extragalactic sources.

5 SUMMARY

We have used interferometric wide-field imaging techniques to image seven of the brightest and most extended sources in the 20 GHz southern sky region $-30° > \delta$, with the goal of enhancing the statistical total intensity and polarization samples of Massardi et al. (2008) and Burke et al. (in preparation). The data analysis included flux density and polarization measurements and maps for each of the seven sources. The images have revealed clearly detected 20-GHz emission from all galactic nuclei except that of PKS 2153−69. In all cases, the fractional polarization of the galactic core was not detected or less than 1 per cent (in the case of Centaurus A and PKS 1333−33). While edge-brightening and a perpendicularity of electric field polarization vectors to brightness isocountours was observed in some sources, the lack of such features in compact jet regions supported the hypothesis that the features may be due to re-orientation of field geometries across broad lobe and hotspot components. All sources for which we imaged the entire source had declining spectra across 5 to 18 GHz at an average spectral index of $-0.88$.

PKS 1333−33 was one of the three sources exhibiting detected polarization in its core, and it showed a perpendicular jet geometry to the close jets spanning the core. The jets exhibited a transverse magnetic field configuration to the jet axis, a feature usually observed in BL Lacertae objects. Centaurus B exhibited a similar change in alignment between its core and outer regions with very little variation in angle along the peaks of the eastern and western hotspot regions, however, the smaller scale jets did not have detectable polarization.

We have put forward Pictor A as an excellent extragalactic calibrator candidate for the ESO Planck satellite mission that aims to measure the polarized signature of the CMB. Pictor A’s integrated polarized intensity at $0.50 \pm 0.06$ Jy, its total intensity of $6.32 \pm 0.11$ Jy, its position in the sky and its angular size contribute to its suitability as a candidate.

ACKNOWLEDGMENTS

RDE is the recipient of an Australian Research Council Federation Fellowship, which also provided financial support for SBS. MM wishes to recognize the financial support from ASI and MUR. TM acknowledges the support of an ARC Australian Postdoctoral Fellowship (DP0665973).

REFERENCES

Bennet C. L. et al., 2003, ApJS, 148, 97
Berge G. L., Sieistad G. A., 1967, ApJ, 148, 367
Bersanelli M., Mandolesi N., 2000, Astrophys. Lett. Commun., 37, 171
Boehringer H., Neumann D. M., Schindler S., Kraan-Korteweg R. C., 1996, ApJ, 467, 168
Bolton J. G., Stanley G. J., Slee O. B., 1949, Nat, 164, 101
Bolton J. G., Gardner F. F., Mackey M. B., 1964, Aust. J. Phys., 17, 340
Brown D. L., Burns J. O., 1991, AJ, 102, 1917
Burgess A. M., Hunstead R. W., 2006, AJ, 131, 114
Caon N., Capaccioli M., D’Onofrio M., 1994, A&AS, 106, 199
Christiansen W. N., Fraser R. H., Watkinson A., O’Sullivan J. D., Lockhart I. A., Goss W. M., 1977, MNRAS, 181, 183
Colbert J. W., Mulchaey J. S., Zabludoff A. I., 2001, AJ, 121, 808
Condon J. J., Griffith M. R., Wright A. E., 2003, ApJ, 106, 1095
Cooper B. F. C., Price R. M., Cole D. J., 1965, Aust. J. Phys., 18, 589
Cornwell T. J., 2008, IEEE J. Sel. Topics Signal Process., 2, 793
Da Costa L. N., Pellegrini P. S., Davis M., McKeins A., Sargent W. L. W., Tonry J. L., 1991, ApJS, 75, 935
Danziger I. J., Fosbury R. A. E., Penston M. V., 1977, MNRAS, 179, 41r
Ekers R. D., 1969, Aust. J. Phys. Suppl., 6, 3
Ekers R. D., 1970, Aust. J. Phys., 23, 217
Ekers R. D., Goss W. M., Kotanyi C. G., Skellern D. J., 1978, A&A, 69, L21
Ekers R. D., Goss W. M., Wellington K. J., Bosma A., Smith R. M., Schweizer F., 1983, A&A, 127, 361
Emonts B. H. C., Morganti R., Oosterloo T. A., Hold J., Tadhunter C. N., van der Huist J. M., Ojha R., Sadler E. M., 2008, MNRAS, 387, 197
Ferguson H. C., 1989, AJ, 98, 367
Fosbury R. A. E., Morganti R., Wilson W., Ekers R. D., di Serego Alighieri S., Tadhunter C. N., 1998, MNRAS, 290, 701
Gabuzda D. C., Pushkarev A. B., Cawthorne T. V., 2000, MNRAS, 319, 1109
Geldzahler B. J., Neumann D. M., Schindler S., Kraan Korteweg R. C., 1996, A&A, 319, 497
Goss W. M., Wellington K. J., Christiansen W. N., Watkinson A., Frater R. H., Little A. G., Lockhart I. A., 1977, MNRAS, 181, 183
Huchra J. P., Geller M. J., 1982, ApJ, 257, 423
Haves P., 1975, MNRAS, 173, 553
Hu W., Hedman M. M., Zaldarriaga M., 2003, Phys. Rev. D, 67, 043004
Huchra J. P., Geller M. J., 1982, ApJ, 257, 423
Jones P. A., McAdam W. B., 1992, ApJS, 80, 137
Jones P. A., McAdam W. B., 1996, MNRAS, 282, 137
Jones P. A., Lloyd B. D., McAdam W. B., 2001, MNRAS, 325, 817
Junkes N., Haynes R. F., Harnett J. J., Jauncey D. L., 1993, MNRAS, 269, 29

Figure 9. The spectrum of integrated intensity of Pictor A, including measurements from selected literature which have measured its integrated flux density. Overplotted is the spectral fit of Perley et al. (1997).
