

## RADIO-CONTINUUM EMISSION FROM THE YOUNG GALACTIC SUPERNOVA REMNANT G1.9+0.3

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**SUMMARY:** We present an analysis of a new Australia Telescope Compact Array (ATCA) radio-continuum observation of supernova remnant (SNR) G1.9+0.3, which at an age of  $\sim 181 \pm 25$  years is the youngest known in the Galaxy. We analysed all available radio-continuum observations at 6-cm from the ATCA and Very Large Array. Using this data we estimate an expansion rate for G1.9+0.3 of  $0.563\% \pm 0.078\%$  per year between 1984 and 2009. We note that in the 1980's G1.9+0.3 expanded somewhat slower ( $0.484\%$  per year) than more recently ( $0.641\%$  per year). We estimate that the average spectral index between 20-cm and 6-cm, across the entire SNR is  $\alpha = -0.72 \pm 0.26$  which is typical for younger SNRs. At 6-cm, we detect an average of 6% fractionally polarised radio emission with a peak of  $17\% \pm 3\%$ . The polarised emission follows the contours of the strongest of X-ray emission. Using the new equipartition formula we estimate a magnetic field strength of  $B \approx 273 \mu\text{G}$ , which to date, is one of the highest magnetic field strength found for any SNR and consistent with G1.9+0.3 being a very young remnant.

**Key words.** ISM: individual objects: G1.9+0.3 – ISM: supernova remnants – radio continuum: ISM – supernovae: general

### 1. INTRODUCTION

It is widely accepted that current catalogues have a distinct deficit of young Galactic supernova remnants (SNRs), that is, SNRs <2000 years old, with only  $\sim 10$  confirmed out of a predicted  $\sim 50$  (van den Bergh and Tammann 1991, Cappellaro 2003). Of these confirmed SNRs, G1.9+0.3 is of particular

interest as it is believed to be the youngest in the Milky Way (MW), i.e.  $\sim 150$  years old (Reynolds et al. 2008, Green et al. 2008, Reynolds et al. 2009, Carlton et al. 2011a,b).

Originally identified as a probable SNR by Green and Gull (1984) at 4.9 GHz using the Karl G. Jansky Very Large Array (VLA), G1.9+0.3 was described as a shell source with an approximate brightness slightly less than that of the Tycho and Kepler

SNRs with a spectral index of  $\alpha \sim -0.7^1$ . Using the Molonglo Observatory Synthesis Telescope (MOST) Galactic Survey data, Gray (1994) confirmed the classification of G1.9+0.3 as an SNR: the source was described as featuring a shell-like morphology in the radio with an estimated diameter of  $1'.2$ . Later, LaRosa et al. (2000) produced a 90-cm image of G1.9+0.3 using observations from the VLA. They estimated the 20/90-cm spectral index of the SNR to be  $\alpha = -0.93 \pm 0.25$  and the angular diameter to be  $1'.1$ . Nord et al. (2004) revisited the data collected by LaRosa et al. (2000) and – through the application of superior data reduction techniques – measured the diameter of G1.9+0.3 to be  $<1'$  and placed it at a distance of  $<7.8$  kpc. Green (2004) estimates the diameter of G1.9+0.3 based on 1.49 GHz VLA observations made in 1985 to be  $1'.2$ . Most recently, Roy and Pal (2014) measured the HI absorption distance using known anomalous velocity features near the Galactic Centre (GC) and found a lower limit on G1.9+0.3 distance from Sun as 10 kpc, some 2 kpc further away from the GC. Therefore, multiple radio observations have confirmed that G1.9+0.3 has the smallest angular diameter for a known Galactic SNR, indicative of its young age.

Green et al. (2008) re-observed G1.9+0.3 at 4.86 GHz using the VLA after Reynolds et al. (2008) used 2007 *Chandra* images to show G1.9+0.3 had expanded significantly since 1985 and its X-ray emission appeared to be predominantly synchrotron in nature. By comparing these new VLA observations with the 1985 VLA observations made at 1.49 GHz, Green et al. (2008) determined that G1.9+0.3 had expanded by  $15\% \pm 2\%$  over 23 years ( $\sim 0.65\%$  per year). Using the same VLA observations from 1985 and 1989, Gómez and Rodríguez (2009) derived an expansion rate of  $0.46\% \pm 0.11\%$  and an age of  $220 \pm_{45}^{70}$  years. By comparing 2007 and 2009 *Chandra* X-ray images and utilising a simple uniform-expansion model, Carlton et al. (2011a,b) find an expansion rate of  $0.642\% \pm 0.049\% \text{ yr}^{-1}$  and a flux increase of  $1.7\% \pm 1.0\% \text{ yr}^{-1}$ , ageing the remnant at  $156 \pm 11$  yr assuming no deceleration. Murphy, Gaensler and Chatterjee (2008) found that G1.9+0.3's flux density at 843 MHz increased by  $1.22 \pm_{0.16}^{0.24} \%$  per year over the last two decades.

Borkowski et al. (2013) suggest that G1.9+0.3 was likely a Type Ia SNe with the shell of its remnant in free expansion with a velocity  $\sim 18000 \text{ km s}^{-1}$ . The ejecta shows spatial asymmetry with prominent Fe-group elements in the northern rim. Also, we point out that Abramowski et al. (2014) report no  $\gamma$ -ray signal from G1.9+0.3 using observations from the H.E.S.S. (High Energy Stereoscopic System) Cherenkov telescope array.

The presence of polarised emission and spatial spectral variations are identified by Farnes (2012), with flatter spectra identified in the NW and SE of the remnant.

In this paper, we present the results of our Australia Telescope Compact Array (ATCA) radio-continuum observations of G1.9+0.3 made at 20, 13 and 6 cm in 2009. A comprehensive expansion study is conducted by comparing the new 6-cm observations with a previously unpublished 6-cm ATCA radio-continuum observation, made in 1993, and three 6-cm VLA observations made in 2008, 1989 and 1984 respectively. We also report on the radio-continuum spectral energy distribution and polarisation properties of this young SNR.

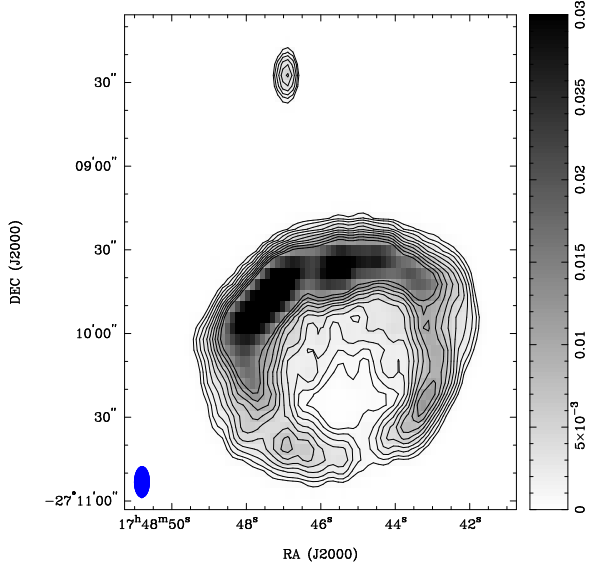
## 2. OBSERVATIONAL DATA

G1.9+0.3 was observed at 20, 13 and 6 cm wavelengths on four days in 2009 (Project C1952). Two of those days being in January 2009 with the remainder in February 2009. The 20-cm and 13-cm observations, taken on the 2nd and 3rd day, were carried out simultaneously as they make use of a common feed-horn. The 6-cm observations taken on the 1st and 4th day, used four different frequencies (two per day) to improve multi-frequency synthesis (MFS). For this purpose, the MIRIAD (Sault and Killeen 2008) task MFPLAN was used to select the most appropriate frequencies. Over the four days G1.9+0.3 was observed with two separate antenna configurations for a total of 29 independent baselines covering a range of spacings from 31 to 6000 m. See Table 1 for complete observational details.

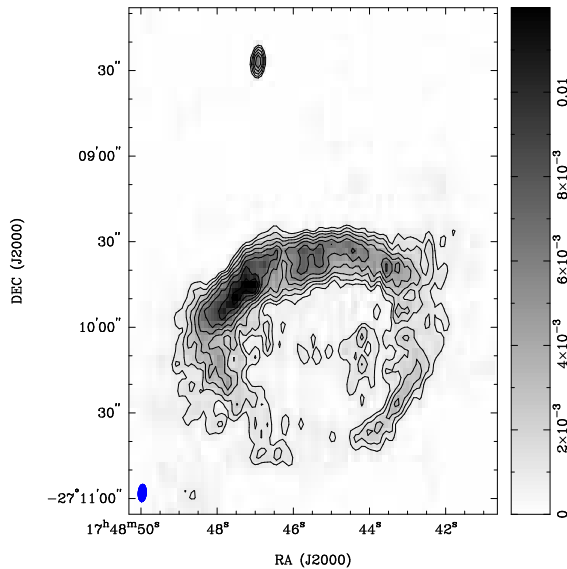
**Table 1.** 2009 ATCA observations of G1.9+0.3.

	Day 1	Day 2	Day 3	Day 4
Date	03 Jan	04 Jan	06 Feb	07 Feb
ATCA Array	6C	6C	EW352	EW352
Frequency 1	4.672 GHz	1.384 GHz	1.384 GHz	4.544 GHz
Frequency 2	5.440 GHz	2.368 GHz	2.368 GHz	5.184 GHz
Bandwidth	128 MHz	128 MHz	128 MHz	128 MHz
Time on source	332 min	458 min	509 min	1033 min
Primary Calibrator	J1934-638	J1934-638	J1934-638	J1934-638
Secondary Calibrator	J1741-312	J1751-253	J1751-253	J1741-312

<sup>1</sup>Spectral index defined as  $S \propto \nu^\alpha$



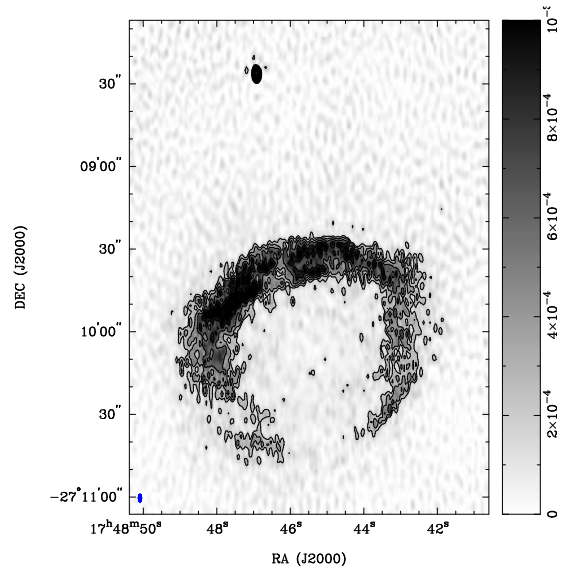
**Fig. 1.** ATCA 20-cm image of Galactic SNR G1.9+0.3. The blue ellipse in the lower left corner represents the synthesised beam of  $10''.9 \times 5''.4$  at  $PA = -0^\circ.5$ . Contours are drawn at  $3\sigma$ ,  $5\sigma$ ,  $8\sigma$ ,  $12\sigma$ ,  $17\sigma$ ,  $23\sigma$ ,  $30\sigma$ ,  $38\sigma$ ,  $47\sigma$  and  $57\sigma$  ( $\sigma = 0.22$  mJy/beam).



**Fig. 2.** ATCA 13-cm image of Galactic SNR G1.9+0.3. The blue ellipse in the lower left corner represents the synthesised beam of  $6''.1 \times 2''.9$  at  $PA = -0^\circ.5$ . Contours are drawn at  $3\sigma$ ,  $5\sigma$ ,  $8\sigma$ ,  $12\sigma$ ,  $17\sigma$ ,  $23\sigma$ ,  $30\sigma$ ,  $38\sigma$ ,  $47\sigma$  and  $57\sigma$  ( $\sigma = 0.32$  mJy/beam).

In Figs. 1 through 3 we show our new ATCA 2009 images of G1.9+0.3 at 20-cm, 13-cm and 6-cm respectively. All these images were formed us-

ing MFS with uniform weighting and were deconvolved using the MIRIAD (Sault and Killeen 2008) CLEAN and RESTOR tasks, with self calibration being applied to the 6-cm image only. We note that our corresponding ATCA flux density measurements are significantly smaller ( $\sim 50\%$ ) than the VLA estimates of Green et al. (2008). We can attribute this large difference to missing short spacings and poorer  $uv$  coverage of the ATCA images.



**Fig. 3.** ATCA 6-cm image of Galactic SNR G1.9+0.3. The blue ellipse in the lower left corner represents the synthesised beam of  $2''.8 \times 1''.2$  at  $PA = -0^\circ.5$ . Contours are drawn at  $3\sigma$ ,  $5\sigma$ ,  $8\sigma$ ,  $12\sigma$ ,  $17\sigma$ ,  $23\sigma$ ,  $30\sigma$ ,  $38\sigma$ ,  $47\sigma$  and  $57\sigma$  ( $\sigma = 0.07$  mJy/beam).

### 3. RESULTS

#### 3.1. G1.9+0.3 Expansion and Age

A simple way to determine the age (in years) of a young SNR is to compare two images of the SNR taken at different epochs and to measure the percentage expansion the SNR has undergone over the time between the observations. Since we know that the SNR will have expanded by 100% in the intervening period between the SN explosion and the later observation, we can apply the simple formula,  $\text{Age} = 100\% / \text{ER}$ , where ER is the percentage expansion the SNR has undergone over the time between the observations (in years).

Ideally, to most accurately determine the expansion rate of an SNR, one should compare images from similar observations i.e., at the same wavelength and having similar, if not identical,  $uv$ -coverage, resolution and  $rms$  noise.

In the case of G1.9+0.3 the first observations were made in 1984 using the VLA, with the best image produced from the 6 cm data (Fig. 4, bottom left). With this in mind, ATCA and VLA archives

**Table 2.** VLA observations of G1.9+0.3.

	1984 obs.	1989 obs.	2008 obs.
Date	26 May 1984	23 June 1989	12 March 2008
VLA Array	C	BC	C
Frequency	4.89 GHz	4.89 GHz	4.89 GHz
Bandwidth	50 MHz	50 MHz	50 MHz
Time on source	~10 min	~10 min	~30 min
Primary Calibrator	3C286	3C286	3C286
Secondary Calibrator	J1832-105	J1751-253	J1751-253

were searched for all available radio-continuum data of G1.9+0.3 made at this same wavelength of 6 cm.

For the expansion study carried out in this paper, one ATCA and three VLA observations made at 6-cm were found at different epochs from the original 1984 to 2008.

The archival ATCA observation was taken on the 10<sup>th</sup> June 1993 (Project C034; P.I.: A. Gray). This observation was made in the 6-cm band centred at 4672 and 5440 MHz with a bandwidth (BW) of 128 MHz and the telescope in 6A configuration<sup>2</sup>. Source 1934-638 was used for primary calibration and source 1748-253 was used for secondary calibration. The observations were done in the so-called "snap-shot" mode, totalling ~1 hour of integration spread equally over a 12 hour period. With very few short baselines and poor *uv*-coverage, resulting *rms* of 0.2 mJy beam<sup>-1</sup> is the highest amongst all the analysed observations. Consequently, the data for this observation are of very poor quality and, while the results are still presented here, we exclude measurements from this image in our determination of expansion rates and age. The archival VLA observations were from the 1984 (Project AG0146), 1989 (Project AB0544) and 2008 (project AG0793), see Table 2 for details.

All these observations of G1.9+0.3 were reduced and analysed with the MIRIAD (Sault, Teuben and Wright 1995) and KARMA (Gooch 1995) software packages.

As the resolutions of the produced images varied (due to the various array configuration, observational periods and therefore resultant *uv*-coverage), the resolutions of all the images were smoothed/convolved to match the image with the lowest resolution (9'' × 4'' at a PA of 0°), see Fig. 4.

Since the *rms* noise of the resultant images also varied (see Table 3), it was decided not to try to determine the expansion by looking at how the shock front moved between epochs, but by looking at how the radially averaged shell profile peak moved from epoch to epoch.

Using RA=17<sup>h</sup>48<sup>m</sup>45<sup>s</sup>.4, Dec=-27°10'06'' as the centre of G1.9+0.3 we produced normalised shell profiles (Fig. 5), averaged over all angles, for each of the images shown in Fig. 4.

**Table 3.** G1.9+0.3 *rms* noise (1σ) of 6 cm images shown in Fig. 4. All five images shown in Fig. 4 have matched resolution of 9''×4'' at a PA of 0°.

Telescope	Date	Image <i>rms</i> (mJy/beam)
VLA	1984	0.09
VLA	1989	0.09
ATCA	1993	0.20
VLA	2008	0.06
ATCA	2009	0.06

From the shell profiles in Fig. 5 we have determined the expansion rate in arc-seconds per year, percentage expansion per year, the averaged expansion velocity in km s<sup>-1</sup> (assuming a distance of 8.5 kpc<sup>3</sup>), and age in years. These results are summarised in Tables 4 though 7, respectively.

**Table 4.** Expansion rate of G1.9+0.3 in arc-seconds per year of radially averaged radio-continuum emission peak.

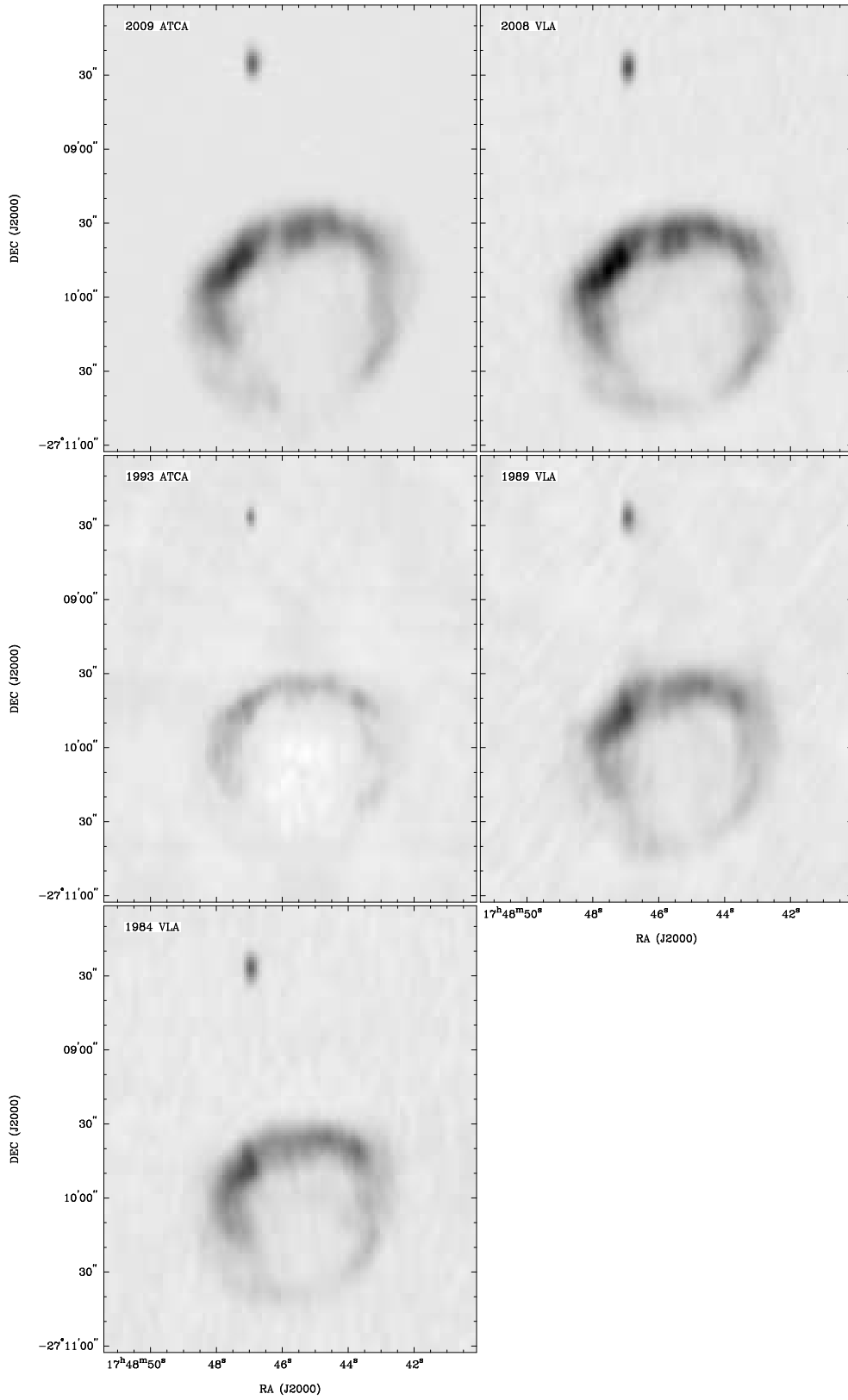
	1984	1989	2008	2009
1984	0			
1989	0.148	0		
2008	0.189	0.200	0	
2009	0.182	0.191	0	0

**Table 5.** % Expansion of G1.9+0.3 per year of radially averaged radio-continuum emission peak.

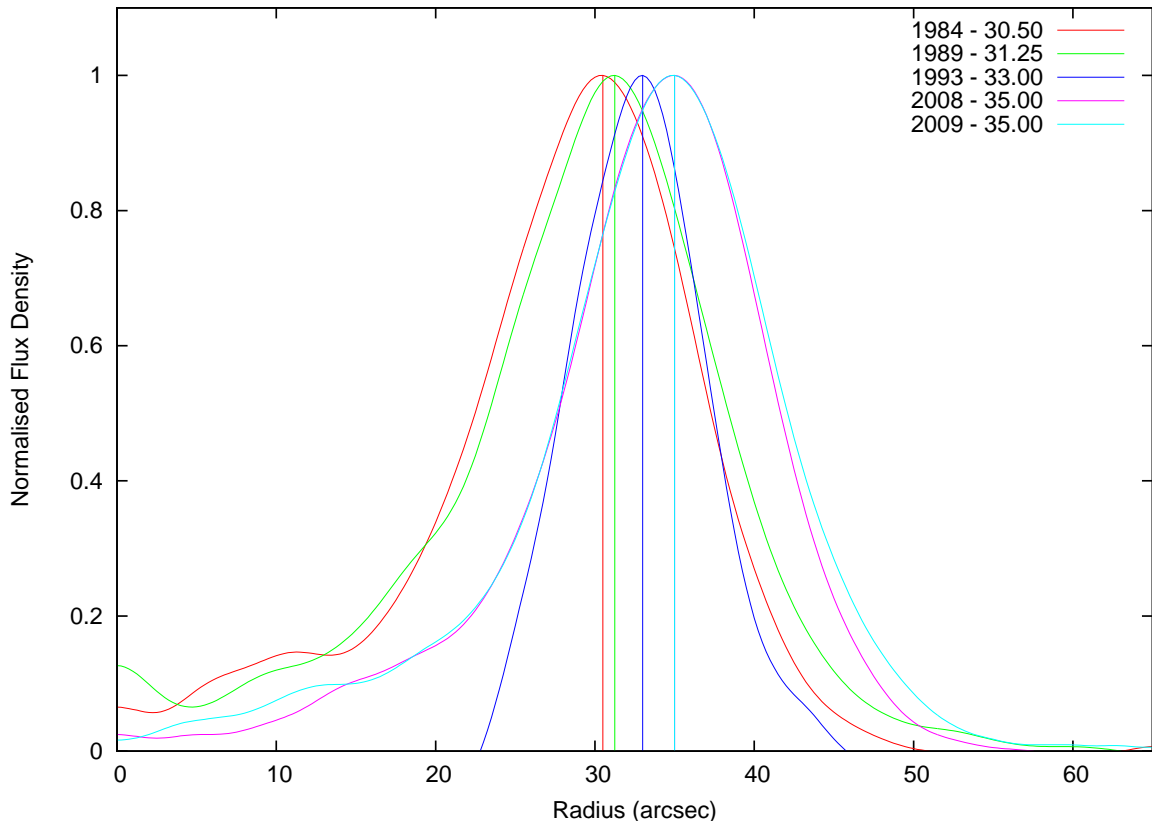
	1984	1989	2008	2009
1984	0			
1989	0.484	0		
2008	0.620	0.641	0	
2009	0.598	0.612	0	0

<sup>2</sup>We combined these two frequencies into a single 1 GHz band, see the image shown in Fig. 4 (middle left).

<sup>3</sup>Distance estimates to G1.9+0.3 vary between ~7.8 kpc (Nord et al. 2004) and 10 kpc (Roy and Pal 2014). We use 8.5 kpc as the most likely distance – suggested by Reynolds et al. (2008).



**Fig. 4.** Matched resolution ( $9'' \times 4''$  at a PA of  $0^\circ$ ) 6-cm images of Galactic SNR G1.9+0.3 (centred at  $RA(J2000)=17^h48^m45^s.4$ ,  $Dec(J2000)=-27^\circ10'06''$ ) at multiple epochs. Left to right, top to bottom, 2009 ATCA, 2008 VLA, 1993 ATCA, 1989 VLA and 1984 VLA.



**Fig. 5.** Normalised shell profiles averaged over all angles for each image of G1.9+0.3 in Fig. 4.

**Table 6.** Estimated age of G1.9+0.3 in years.

	1984	1989	2008	2009
1984	0			
1989	206	0		
2008	161	156	0	
2009	167	163	0	0

**Table 7.** Speed of radially averaged radio-continuum emission peak in  $\text{km s}^{-1}$  of G1.9+0.3.

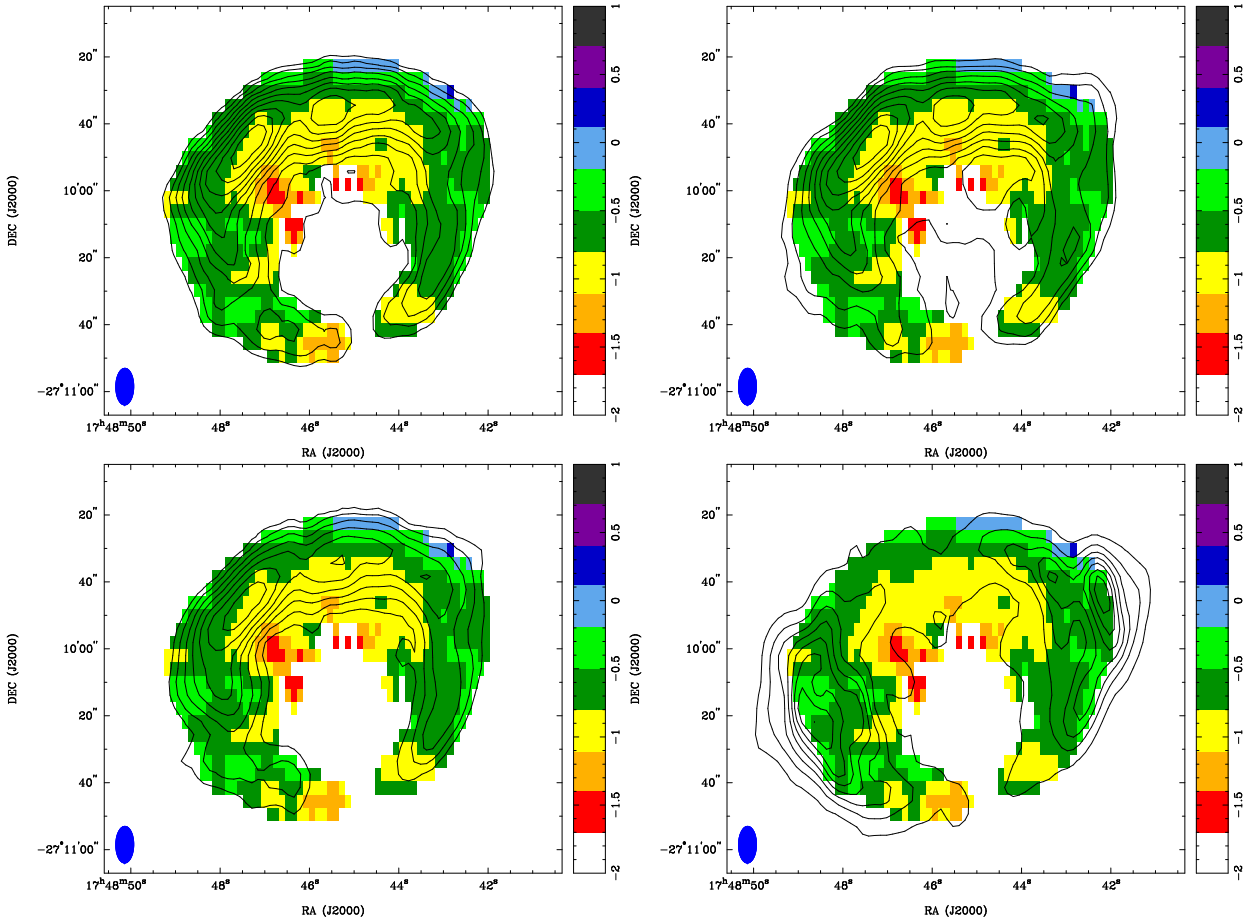
	1984	1989	2008	2009
1984	0			
1989	5 950	0		
2008	7 620	8 070	0	
2009	7 350	7 710	0	0

In Tables 4 and 5 we show the expansion of G1.9+0.3 over the period between 1984 and 2009. The mid range expansion over this period (excluding the 1993 observations) is  $0.563\% \pm 0.078\% \text{ yr}^{-1}$  or  $0.174 \pm 0.026 \text{ arcsec yr}^{-1}$ . However, we note that between 1984 and 1989, G1.9+0.3 expanded at a somewhat slower rate ( $0.484\% \text{ yr}^{-1}$ ) which was also estimated by Gómez and Rodríguez (2009) at  $0.46\% \pm 0.11\%$  based on 20-cm VLA data from the same period. Since 1989, G1.9+0.3 appears to expand at a faster rate of up to  $0.641\%$  per year which

is in excellent agreement with the X-ray estimates of Carlton et al. (2011a,b) of  $0.642\% \pm 0.049\%$  and Green et al. (2008) using VLA observations. This may be an indication that perhaps the shock has "broken through" to a region of lower density and thus accelerated. The mid range expansion rate derived here, yields an upper age limit of  $181 \pm 25$  years (Table 6) assuming a constant expansion rate since the SN event. This dates the SN event back to the year 1828 ( $\pm 25$ ).

Similarly, the speed at which the radially averaged radio-continuum emission peak is moving (assuming a distance to G1.9+0.3 of 8.5 kpc) is somewhat slower in the 1980's ( $\sim 6\,000 \text{ km sec}^{-1}$ ) than later, when it speeds up to  $\sim 8\,000 \text{ km sec}^{-1}$  (Table 7). The speed of radially averaged radio-continuum emission peak should not be confused with the expansion velocity of the SNR shock front, which has been estimated at  $\sim 18\,000 \text{ km sec}^{-1}$  by Borkowski et al. (2013).

As our determination of the radially averaged radio-continuum emission peak speed is dependent on the distance to the SNR we estimate that at the lower end (between 1984 and 1989) the speed varies between  $5\,500 \text{ km sec}^{-1}$  (at a distance of 7.8 kpc) and  $7\,000 \text{ km sec}^{-1}$  (at a distance of 10 kpc). More recently (between 1989 and 2009), the speed varies between  $7\,400 \text{ km sec}^{-1}$  (at a distance of 7.8 kpc) and  $9\,500 \text{ km sec}^{-1}$  (at a distance of 10 kpc).



**Fig. 6.** The Spectral Index map of G1.9+0.3 overlaid with 20-cm contours (top left; contours are: 3, 5, 8, 12, 12, 17, 23, 30, 38, 47, 57  $\times 7.5 \times 10^{-4}$  Jy/beam), 13-cm contours (top right; contours are: 3, 5, 8, 12, 17, 23, 30, 38, 47, 57  $\times 6.0 \times 10^{-4}$  Jy/beam), 6-cm contours (bottom left; contours are: 3, 5, 8, 12, 17, 23, 30  $\times 5.0 \times 10^{-4}$  Jy/beam) and 2007 Chandra X-ray contours (bottom right; contours are: 33.57, 67.14, 100.7, 134.3, 167.9, 201.4, 235, 268.6 cts/s).

### 3.2. G1.9+0.3 Spectral Energy Distribution

By matching the resolutions of our 2009 ATCA images at 6-cm and 13-cm to that of the 20-cm image ( $10''.9 \times 5''.4$  at PA= $-0^\circ 5$ ), a three point spectral index map was created, allowing for the examination of the spatial spectral variations in the remnant (see Fig. 6). In this map, the colour of each pixel represents the spectral index  $\alpha$  across the three observational frequencies.

From this map we can see that the radio-continuum spectral energy distribution across the NW and SE regions is flatter ( $\alpha \sim -0.5$ ) which is also following the contours of the strongest of X-ray emission (so called "X-ray ears" of G1.9+0.3; see Fig. 6 – bottom right). This SED flattening in the NW and SE is also confirmed by Farnes (2012) in his VLA observations. The steeper ( $\alpha \sim -1$ ) radio spectra is dominant in the Northern region of

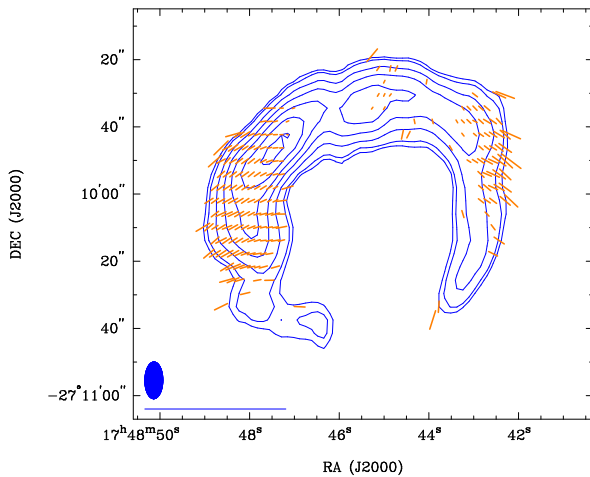
G1.9+0.3 corresponding to where the radio emission is the strongest and therefore indicating the synchrotron radio-continuum emission. We also note that a somewhat steeper spectral index ( $\alpha < -1.0$ ) is dominating the inside part of the SNR, while flatter spectra is at the edges.

We estimate that the average spectral index across the entire SNR is  $\alpha = -0.72 \pm 0.26$  which is flatter than LaRosa et al. (2000) ( $\alpha = -0.93 \pm 0.25$ ), however, their estimates are based on 20/90 cm flux density measurements. This may indicate that the synchrotron emission may be even more dominant at higher wavelengths (92 cm). Using Green et al. (2008) flux density estimates at 20 and 6 cm from their 2008 VLA observations, we estimate the spectral index  $\alpha = -0.62 \pm 0.08$  which is in good agreement with our ATCA estimates from approximately one year later. This steeper spectral index is expected for younger SNRs (Bell et al. 2011), and further confirms its young age.

### 3.3. Polarisation of G1.9+0.3

Since the ATCA observations recorded Stokes parameters  $Q$ ,  $U$  and  $V$ , in addition to total intensity  $I$ , we were able to determine the polarisation of G1.9+0.3. In our 6-cm image (Fig. 7) we show the regions of polarised emission for G1.9+0.3. The electric field vectors follow the shell of the SNR, around most of the circumference of the SNR, particularly along its eastern side.

The maximum fractional polarisation is estimated to be  $P = 17 \pm 3\%$  with a mean of 6%. No reliable polarisation was detected at 20 or 13 cm. This might indicate a significant depolarisation in the remnant, however the polarimetric response of the ATCA is known to be poor at 13-cm.



**Fig. 7.** 6-cm ATCA observations of G1.9+0.3. The blue ellipse in the lower-left corner represents the synthesised beam width of  $10''.940 \times 5''.384$  at  $PA = -0.5$ . The length of the vectors represents the fractional polarised intensity at each pixel position, and their orientations indicate the mean PA of the electric field (averaged over the observing bandwidth, not corrected for any Faraday rotation). The blue line below the beam ellipse represents the length of a polarisation vector of 100%. The maximum fractional polarisation is  $17\% \pm 3\%$  with a mean of 6%. Contours at 2.2, 2.8, 4.4, 6.6, 9.4, 13, 17, 21, 26 and 32 mJy beam $^{-1}$ ).

Typically, young type Ia SNRs exhibit a radially oriented magnetic field (tangentially oriented electric field), which is to be expected from Rayleigh-Taylor instabilities in a decelerating remnant (Gull 1975, Chevalier 1976). This is consistent with similarly young Galactic SNRs, as well as in the LMC (e.g. Table 3 in Bozzetto *et al.* (2014)). As we have plotted electric field vectors, we would expect them to be tangential to the circumference of the remnant. We can see in Fig. 7, the orientation of the electric field vectors roughly follow this arrangement, how-

ever, it can be seen that this pattern is not strictly followed around the entire remnant. Given the location of G1.9+0.3, towards the Galactic centre, this is most likely due to Faraday depolarisation.

Farnes (2012) also detected the presence of polarised emission. Our ATCA polarimetric results also suggest that the above observed variation is most consistent with an ambient B field perpendicular to the axis of bilateral symmetry indicated by Farnes (2012). Moreover, Farnes (2012) argues that the increased ordering of the B field in the NW as the strong Faraday depolarisation must also be present.

Farnes (2012) also argues that an intrinsically radially-oriented field could be provided by a systematic gradient in Rotation Measure (RM) of  $140 \text{ rad m}^{-2}$  from N to S and can also explain the depolarisation that we observe in our ATCA images.

### 3.4. Magnetic Field of G1.9+0.3

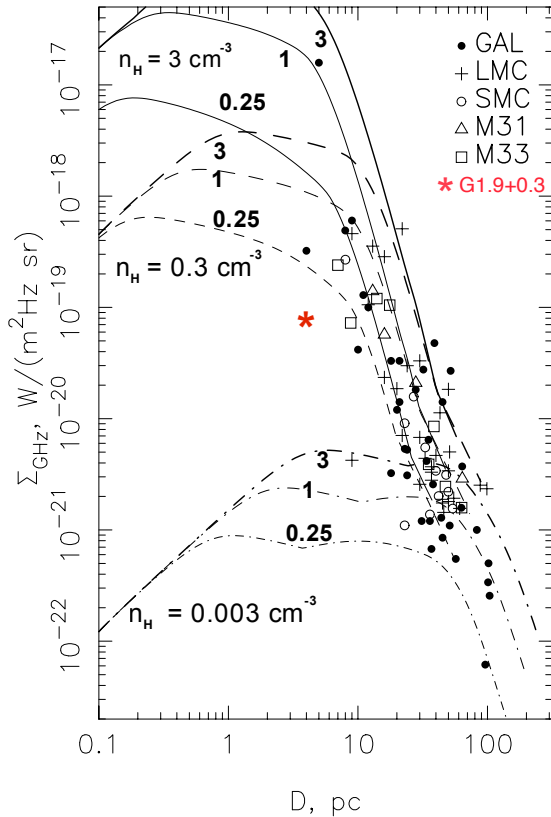
We used the new equipartition formulae derived by Arbutina *et al.* (2012, 2013) based on the diffusive shock acceleration (DSA) theory of Bell (1978) to estimate a magnetic field strength. These formulae are particularly relevant to magnetic field estimation in SNRs, and yield magnetic field strengths between those given by the classical equipartition (Pacholczyk 1970) and revised equipartition (Beck and Krause, 2005) methods. We estimate the magnetic field strength of G1.9+0.3 to be  $B \approx 273 \mu\text{G}$  and the minimum total energy of the synchrotron radiation to be  $E_{\text{min}} \approx 1.8 \times 10^{48}$  ergs (see Arbutina *et al.* 2012, 2013); and corresponding online calculator<sup>4</sup>). For this estimate, we used a spectral index value of  $\alpha = -0.72$ , integrated flux density  $S_{1.425} = 0.935 \text{ Jy}$  at  $\nu = 1.425 \text{ GHz}$  (Green *et al.* 2008), distance  $D = 8.5 \text{ kpc}$ , SNR radius of  $r = 46''$  and filling factor of 0.33. However, if we additionally assume a shock velocity of  $18000 \text{ km s}^{-1}$  (as suggested by Borkowski *et al.* (2013)) than the magnetic field strength of G1.9+0.3 becomes somewhat lower ( $B \approx 180 \mu\text{G}$ ) and the minimum total energy of the synchrotron radiation is  $E_{\text{min}} \approx 7.6 \times 10^{47}$  ergs. These estimates are very similar to Arbutina *et al.* (2012) estimates of  $B \approx 228 \mu\text{G}$  and  $E_{\text{min}} \approx 9.3 \times 10^{47}$  ergs.

A large magnetic field strength such as this ( $273 \mu\text{G}$ ) is expected for a young SNR (Bell 2004). Indeed, this makes G1.9+0.3 a remnant with one of the highest estimated magnetic field strengths known to date. For example, other young Galactic SNRs (Beck and Krause 2005, Arbutina *et al.* 2012 (see their Table 1)), such as Cas A ( $B \approx 1250 \mu\text{G}$ ), Kepler ( $B \approx 414 \mu\text{G}$ ), G349.7+0.2 ( $B \approx 523 \mu\text{G}$ ) and Tycho ( $B \approx 285 \mu\text{G}$ ), are known remnants with the strongest magnetic fields. Also, in a Large Magellanic Cloud (LMC) SNR, J0509-6731 (also remnant from a Type Ia SN explosion) at about 400 yrs age has magnetic field strength of  $168 \mu\text{G}$  (Bozzetto *et al.*

<sup>4</sup><http://poincare.matf.bg.ac.rs/~arbo/eqp/>



2014), while the magnetic field of LMC SNR J0519–6902 is  $171 \mu\text{G}$  (Bozzetto et al. 2012). The Small Magellanic Cloud SNR HFK 443 (Crawford et al. 2014, in press) has a field strength of  $90 \mu\text{G}$  with numerous other older remnants falling below these values. It is most likely that G1.9+0.3 is going through an evolutionary stage where the magnetic field has been amplified (added to simple compression by the shocks), which may explain such a high magnetic field value (Telezhinsky et al. 2012). The amplification of magnetic field is a process driven by very fast shocks of young SNRs. Because of the strong amplification of magnetic field, a spectral index of  $\alpha = -0.72$ , and the location in the surface brightness-diameter diagram, this SNR is of younger age, in free expansion stage, and expanding in a low density environment.



**Fig. 8.** 1 GHz surface brightness-to-diameter diagram from Berezhko and Völk (2004), with G1.9+0.3 added. The evolutionary tracks are for ISM densities of  $n_{\text{H}} = 3, 0.3$  and  $0.003 \text{ cm}^{-3}$  and explosion energies of  $E_{\text{SN}} = 0.25, 1$  and  $3 \times 10^{51} \text{ erg}$ .

In Fig. 8 we show a surface brightness–diameter ( $\Sigma - D$ ) diagram at 1 GHz with theoretically-derived evolutionary tracks (Berezhko and Völk 2004) superposed. G1.9+0.3 lies at  $(D, \Sigma) = (3.8 \text{ pc}, 7.5 \times 10^{-20} \text{ W m}^{-2} \text{ Hz}^{-1} \text{ Sr}^{-1})$  in the diagram. Its position on the diagram tentatively suggests that it is in the mid-to-late free expansion phase of evolution — expanding into a low density environment ( $n_{\text{H}} \lesssim 0.3 \text{ cm}^{-3}$ ).

## 4. CONCLUSIONS

Here, we have presented new 6-cm, 13-cm and 20-cm ATCA observations of Galactic SNR G1.9+0.3 made in 2009. Using the new 6-cm data and archival 6-cm data we observe that there are indications that the expansion of G1.9+0.3 accelerated after 1989. Our results are in a broad agreement with the estimates of expansion made by Reynolds et al. (2008), Green et al. (2008), Gómez and Rodríguez (2009) and Carlton et al. (2011a,b). We find that at  $\sim 181$  yrs, G1.9+0.3 is indeed very young and most likely the youngest SNR in the Milky Way. This very young age is also reinforced by the magnetic field arrangement and strength we estimate.

We make the following findings:

- Expansion rate of 0.484% per year between 1984 and 1989;
- Expansion rate of 0.641% per year between 1989 and 2009;
- Expansion rate of  $0.563\% \pm 0.078\%$  per year between 1984 and 2009;
- Age of  $181 \text{ yrs} \pm 25 \text{ yrs}$ ;
- Average spectral index between 20-cm and 6-cm, across the entire SNR is  $\alpha = -0.72 \pm 0.26$ ;
- 6% fractionally polarised radio emission with a peak of  $17\% \pm 3\%$ ;
- Magnetic field strength  $B \approx 273 \mu\text{G}$ ;

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## REFERENCES

- Abramowski, A. and H. E. S. S. Collaboration et al.: 2014, *Mon. Not. R. Astron. Soc.*, **441**, 790.
- Arbutina B., Urošević D., Andjelić M. M., Pavlović, M. Z. and Vukotić B.: 2012, *Astrophys. J.*, **746**, 79.
- Arbutina B., Urošević D., Vučetić M. M., Pavlović, M. Z. and Vukotić B.: 2013, *Astrophys. J.*, **777**, 31.
- Beck, R. and Krause, M.: 2005, *Astron. Nachr.*, **326**, 414.
- Bell, A. R.: 1978, *Mon. Not. R. Astron. Soc.*, **182**, 443.
- Bell, A. R.: 2004, *Mon. Not. R. Astron. Soc.*, **353**, 550.
- Bell, A. R., Schure K. M. and Reville B.: 2011, *Mon. Not. R. Astron. Soc.*, **418**, 1208.
- Berezhko, E. G. and Völk, H. J.: 2004, *Astron. Astrophys.*, **427**, 525.

- Borkowski, K. J., Reynolds, S. P., Hwang, U., Green, D. A., Petre, R., Krishnamurthy, K. and Willett, R.: 2013, *Astrophys. J.*, **771**, L9.
- Bozzetto, L. M., Filipović, M. D., Urošević, D. and Crawford, E. J.: 2012, *Serb. Astron. J.*, **185**, 25.
- Bozzetto, L. M., Filipović, M. D., Urošević, D., Kothes, R. and Crawford, E. J.: 2014, *Mon. Not. R. Astron. Soc.*, **440**, 3220.
- Cappellaro, E.: 2003, in "Supernovae and Gamma-Ray Bursters", ed. Weiler K., Lecture Notes in Physics, Berlin Springer Verlag, Vol. **598**, 37.
- Carlton, A. K., Borkowski, K. J., Reynolds, S. P., Willett, R., Krishnamurthy, K., Green, D. A. and Petre, R.: 2011a, in American Astronomical Society Meeting Abstracts 217. p. 256.12.
- Carlton, A. K., Borkowski, K. J., Reynolds, S. P., Hwang, U., Petre, R., Green, D. A., Krishnamurthy, K. and Willett, R.: 2011b, *Astrophys. J.*, **737**, L22.
- Chevalier, R. A.: 1976, *Astrophys. J.*, **207**, 872.
- Farnes, J.: 2012, PhD thesis, University of Cambridge.
- Gooch, R. E.: 1995, in Astronomical Data Analysis Software and Systems IV, ASP Conf. Series ed. Shaw, R. A., Payne, H. E. and Hayes, J. J. E., **77**, 144.
- Gray, A. D.: 1994, *Mon. Not. R. Astron. Soc.*, **270**, 835.
- Green, D. A. and Gull, S. F.: 1984, *Nature*, **312**, 527.
- Green, D. A.: 2004, *Bull. Astr. Soc. India*, **32**, 335.
- Green, D. A., Reynolds, S. P., Borkowski, K. J., Hwang, U., Harrus, I. and Petre, R.: 2008, *Mon. Not. R. Astron. Soc.*, **387**, L54.
- Gómez, Y. and Rodríguez, L. F.: 2009, *Rev. Mex. Astron. Astrofis.*, **45**, 91.
- Gull, S. F.: 1975, *Mon. Not. R. Astron. Soc.*, **171**, 263.
- LaRosa, T. N., Kassim, N. E., Lazio, T. J. W. and Hyman, S. D.: 2000, *Astron. J.*, **119**, 207.
- Murphy, T., Gaensler, B. M. and Chatterjee, S.: 2008, *Mon. Not. R. Astron. Soc.*, **389**, L23.
- Nord, M. E., Lazio, T. J. W., Kassim, N. E., Hyman, S. D., LaRosa, T. N., Brogan, C. L. and Duric, N.: 2004, *Astron. J.*, **128**, 1646.
- Pacholczyk, A. G.: 1970, in "Radio astrophysics. Nonthermal processes in galactic and extragalactic sources", ed. A. G. Pacholczyk (San Francisco: Freeman).
- Reynolds, S. P., Borkowski, K. J., Green, D. A., Hwang, U., Harrus, I. and Petre, R.: 2008, *Astrophys. J.*, **680**, L41.
- Reynolds, S. P., Borkowski, K. J., Green, D. A., Hwang, U., Harrus, I. and Petre, R.: 2009, *Astrophys. J.*, **695**, L149.
- Roy, S. and Pal, S.: 2014, in "Supernova environmental impacts", eds. Ray A. and McCray R. A., IAU Symposium Vol. **296**, 197.
- Sault, B. and Killeen, N.: 2008, Miriad Users Guide. Australia Telescope National Facility.
- Sault, R. J., Teuben, P. J. and Wright, M. C. H.: 1995, in "Astronomical Data Analysis Software and Systems IV ASP Conference Series", eds. Shaw, R. A., Payne, H. E. and Hayes, J. J. E., **77**, 433.
- Telezhinsky, I., Dwarkadas, V. V. and Pohl, M.: 2012, *Astropart. Phys.*, **35**, 300.
- van den Bergh, S. and Tammann, G. A.: 1991, *Annu. Rev. Astron. Astrophys.*, **29**, 363.

РАДИО-КОНТИНУУМ ЕМИСИЈА МЛАДОГ  
ГАЛАКТИЧКОГ ОСТАТКА СУПЕРНОВЕ G1.9+0.3

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*Оригинални научни рад*

У овој студији представљамо нова радио-континуум посматрања телескопом АТСА на 6 cm најмлађег остатка супернових (ОС) у нашој Галаксији. Анализирана су и сва доступна АТСА и VLA посматрања на овој фреквенцији. Остатак G1.9+0.3 је  $\sim 181 \pm 25$  година стар и годишња стопа раста му је  $0.563\% \pm 0.078\%$  у периоду између 1984. и 1989. Приметили смо да се између 1984. и 1989. остатак ширио нешто спорије ( $0.484\%$  годишње) него после 1989., када је експанзија

достигла ниво од  $0.641\%$  годишње. G1.9+0.3 има типичан радио-спектар за младе остатке са  $\alpha = -0.72 \pm 0.26$ . G1.9+0.3 емитује просечно  $6\%$  поларизованог зрачења на таласној дужини од 6 cm, са максималним интензитетом  $17\% \pm 3\%$ . Ова поларизациона емисија такође тесно прати рендгенско зрачење. Процењено је прилично јако магнетно поље у вредности од  $273 \mu\text{G}$  што представља једно од најснажнијих магнетних поља у до сада посматраним ОС.