Re-identification of G35.6−0.4 as a supernova remnant

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ABSTRACT

G35.6−0.4 is an extended radio source in the Galactic plane which has previously been identified as either a supernova remnant or an H II region. Observations from the Very Large Array Galactic Plane Survey at 1.4 GHz with a resolution of 1 arcmin allow the extent of G35.6−0.4 to be defined for the first time. Comparison with other radio survey observations show that this source has a non-thermal spectral index, with $S \propto \nu^{-0.47 \pm 0.07}$. G35.6−0.4 does not have obvious associated infrared emission, so it is identified as a Galactic supernova remnant, not an H II region. It is $\approx 15 \times 11$ arcmin$^2$ in extent, showing partial limb brightening.

Key words: ISM: individual: G35.6−0.4 – supernova remnants – radio continuum: ISM.

1 INTRODUCTION

There are over two hundred supernova remnants (SNRs) identified in the Galaxy (Green 2004). But current catalogues of SNRs are incomplete, not only due to selection effects, but also because some SNRs have been misidentified in the past, when only limited quality observations were available. As an example, Gaensler et al. (2008) have recently discussed the nature of G350.1−0.3. This radio source in the Galactic plane had been included in catalogues of SNRs—for example Clark & Caswell (1976) and Green (1984)– following its identification as a SNR by Caswell et al. (1975). Subsequently, it was removed from later catalogues of SNRs (Green 1991), following the discussions of Salter et al. (1986), who concluded that it was not possible to define the nature of this source from the then available observations. Gaensler et al. (2008) have presented new observations of G350.1−0.3, including H i absorption observations which show it is Galactic, and conclude that it is after all a young and luminous SNR (although its structure is unusual compared with other Galactic SNRs).

Prompted by this re-assessment, I present here a discussion of another extended Galactic radio source, G35.6−0.4, which was included in early SNR catalogues, but was then removed following its identification as a thermal source. Since G35.6−0.4 is included in the Very Large Array (VLA) Galactic Plane Survey (VGPS; Stil et al. 2006), which has a resolution of 1 arcmin, it is now possible to better define its extent and morphology. Knowing G35.6−0.4’s extent, it is also possible to determine its radio spectrum from available radio surveys that have lower resolution than the VGPS. Moreover, IRAS survey data can be used to distinguish between thermal or non-thermal Galactic sources. Here, I present and discuss the available radio and infrared survey observations of G35.6−0.4, and conclude that it is indeed a SNR, not an H II region.

2 BACKGROUND

G35.6−0.4 is Galactic radio source detected in several early radio surveys (Beard & Kerr 1969; Altenhoff et al. 1970), and listed as a SNR in several early catalogues (Milne 1970; Downes 1971; Ilovaisky & Lequeux 1972; Milne 1979). The extent of the source was given as $\approx 10$ arcmin, although this was not well defined by the available observations, as they had resolutions of only about 7 arcmin at best.

Subsequent radio observations, with somewhat better resolution, provide contradictory information about this source. Both Velusamy & Kundu (1974) and Dickel & Denoyer (1975) derive non-thermal spectral indices for this source, and consequently identify it as a SNR. However, it is difficult to determine accurate flux densities for this source, since it lies on a ridge of emission linking it to a brighter region of thermal radio emission G35.5−0.0 (see below). It is also difficult to compare flux densities derived from surveys with different resolutions when the extent of the source is not well known. On the other hand, Caswell & Clark (1975) – in a study of ‘Observations of radio sources formerly considered as possible supernova remnants’ – derive a flat radio spectral index of $\alpha \approx 0.04$ (using the convention that flux density scale with frequency as $S \propto \nu^{-\alpha}$) from 408-MHz and 5-GHz observations with similar resolution ($\approx 3$ and 4 arcmin, respectively). They regarded G35.6−0.4 as an H II region, not a SNR, and argue that the available upper limit in radio recombination lines (RRLs) did not preclude an H II region identification. [Note that although Dickel & Milne (1972) appear to report a RRL detection from G35.6−0.4 and an upper limit from G35.5−0.0, the labels of these objects had erroneously been swapped, see Dickel & Milne (1973).] Hence, G35.6−0.4 was not included in the SNR catalogue of Clark & Caswell (1976), nor in the first version of my catalogue (Green 1984).

1 Note that this source is mislabelled as G35.5−0.0 in table 1 of Milne (1970).
Angerhofer, Becker & Kundu (1977) also derived a steep non-thermal spectral index of G35.6–0.4, and concluded that it is a SNR. They also found faint polarisation towards it at 5 GHz, but noted that it was not clear if this was associated with the source or from the Galactic background. More recently, Lockman (1989) report a RRL line detection towards $l = 35.588$, $b = -0.489$, and consequently this source – labelled G35.6–0.5 was included as an H ii region in later studies, for example Kuchar & Bania (1990), who made a marginal detection of H i absorption towards it. G35.6–0.5 is also discussed by Phillips & Onello (1993), who describe it as an SNR–H ii region complex, based on Dickel & Milne’s reported RRL detection, and Angerhofer et al. report of non-thermal emission. Phillips & Onello present some further RRL detections towards both G35.6–0.5 and G35.5–0.0, and propose an association between the supposed SNR in the region and the rather old pulsar PSR 1855+02.

### 3 Observations

G35.6–0.4 is included in the region covered by the VGPS, with a resolution of 1 arcmin at 1.4 GHz, see Fig. 1. This provides the highest resolution radio image of the source, which is shown as a partially limb-brightened region of emission $\approx 15 \times 11$ arcmin$^2$. Fig. 1 also shows the emission from the thermal complex G35.5–0.0. The two compact sources within and near G35.6–0.4 are IRAS 18551+0159 (near $l = 35.47$, $b = -0.44$) and IRAS 18554+0203 (near $l = 35.56$, $b = -0.49$), which are a candidate post-asymptotic giant branch star and a planetary nebula, respectively (see Condon, Kaplan & Terzian 1999; Jiménez-Esteban et al. 2005; Parker et al. 2006; Cohen et al. 2007; Kwok et al. 2008 and references therein).

![Figure 1. VGPS image of G35.6–0.4 and its surroundings at 1.4 GHz with a resolution of 1 arcmin, in Galactic coordinates. The contour levels are (black) every 2 K in brightness temperature up to 40 K, then (white) every 10 K. The brighter region of emission towards the top of the plot is the thermal source G35.5–0.0. The star indicates the position of PSR 1855+02. The dashed lines marks the Galactic plane where $b = 0^\circ$.](https://academic.oup.com/mnras/article-abstract/399/1/177/1088085)

The flux density of G35.6–0.4 was estimated from the smoothed VGPS 1.4-GHz and Nobeyama 10-GHz images (i.e. Fig. 2). Polygons were drawn around G35.6–0.4, a tilted plane was fitted to the edges of the polygons and then removed from the image, with the remaining emission within the polygon integrated (see Green 2007). This procedure is subjective in that the results depend on the exact choice of polygon used. In this case, the full-resolution VGPS image was used to define the polygons, bearing in mind the lower resolution of the 10-GHz Nobeyama. Several polygons were used, one of which is shown in Fig. 2 (note that this includes IRAS 18551+0159 which is outside of G35.6–0.4 in the full resolution VGPS image, Fig. 1, but cannot be separated from G35.6–0.4 in the 3 arcmin resolution images). The same polygons were used for both for the 1.4-GHz and 10-GHz images, and it was found that the derived integrated flux densities varied by about 5 per cent at most. The derived flux densities for G35.6–0.4 are: 7.8 and 3.1 Jy at 1.4 and 10 GHz, respectively. Taking a cautious error of 10 per cent in each of the flux densities, these give a spectral index of $\alpha = 0.46 \pm 0.07$ for the radio emission from G35.6–0.4.

Given the previous identifications of G35.6–0.4 as either a SNR or a thermal source, infrared observations allow further discrimination between these possibilities. Fig. 3 shows an IRAS image of G35.6–0.4 at 100 $\mu$m from Improved Reprocessing of the IRAS Survey (IRIS; Miville-Deschênes & Lagache 2005$^3$), compared with a radio image at 2.7 GHz from the Effelsberg survey of Reich et al. (1984)$^4$, which has comparable resolution. Fig. 3 shows infrared emission clearly associated with G35.5–0.0, which is known to be thermal, but no obvious infrared emission from G35.6–0.4.

### 4 Discussion and Conclusions

From the results presented above, G35.6–0.4 can be identified as a SNR, not an H ii region, because of its non-thermal radio spectrum and the lack of extended infra-red emission associated with it. However, the detection of RRL from this source by

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2 see also http://www.ioa.s.u-tokyo.ac.jp/~handa/

3 see also http://irsa.ipac.caltech.edu/data/IRIS/

4 see also http://mpifr-bonn.mpg.de/survey.html
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Figure 2. Images of G35.6−0.4 and its surroundings, in Galactic coordinates. Top: VGPS at 1.4 GHz smoothed to a resolution of 3 arcmin. The contour levels are 2.2 K in brightness temperature. A polygon used to derived an integrated density for G35.6−0.4 is shown (see text). Bottom: Nobeyama survey at 10 GHz from Handa et al. (1987) with a resolution of 3 arcmin. The contour levels are every 0.033 K in brightness temperature.

Figure 3. Images of G35.6−0.4 and its surroundings, in Galactic coordinates. Top: Effelsberg 2.7-GHz image from Reich et al. (1984) with a resolution of 4.3 arcmin. The contour levels are every 0.45 K in brightness temperature. Bottom: IRIS 100-μm image with a resolution of 4.3 arcmin. The grey-scale is 400–3000 MJy sr$^{-1}$.

Lockman (1989) and Phillips & Onello (1993) implies that there is some thermal emission towards this region. But, as noted above, there are indeed two compact IRAS sources within or near G35.6−0.4, with the PN IRAS 18554+0203 being close to the positions where RRLs have been detected.
The VGPS observations (Fig. 1) show that G35.6−0.4 has a partially limb-brightened structure – i.e. it is a ‘shell’ remnant – but with differing radii in different directions, which is reminiscent of the SNR G166.0−4.3 (=VRO 42.05.01), see Landecker et al. (1989). G35.6−0.4 has a 1 GHz surface brightness of \( \approx 8 \times 10^{-21} \) W m\(^{-2}\) Hz\(^{-1}\) sr\(^{-1}\) (for 1 GHz flux density of 9 Jy, and angular size of 15 × 11 arcmin\(^2\)), which is close to what is thought to be the surface brightness completeness limit for current Galactic SNR catalogues (e.g. Green 2004).

Inspection of the H\(_i\) line observations in the VGPS, smoothed to channel resolution of \( \approx 8 \) km s\(^{-1}\), shows absorption towards G35.6−0.4 at positive velocities, up to \( \approx 55 \) km s\(^{-1}\). However, the brightness temperature of the emission from G35.6−0.4 is low, \( \approx 20 \) K above the local background (see Fig. 1), so that faint absorption will not be easily seen. This absorption provides a lower limit to the distance to G35.6−0.4 of \( \approx 3.7 \) kpc (the near distance corresponding to \( \approx 55 \) km s\(^{-1}\), for a simple ‘flat’ rotation curve with a constant velocity of 220 km s\(^{-1}\) and a Galactocentric radius of 8.5 kpc). In the VGPS H\(_i\) line observations, absorption towards the brighter H\(_\Pi\) region G35.5−0.0 can be seen at larger positive velocities, to at least +90 km s\(^{-1}\). The recombination line velocity for this H\(_\Pi\) region is \( \approx 51 \) km s\(^{-1}\) (Lockman 1989), which implies a distance of \( \approx 10.5 \) kpc (i.e. the far distance corresponding to 51 km s\(^{-1}\), since H\(_i\) absorption is seen to larger positive velocities).

If G35.6−0.4 is at the same distance as G35.5−0.0, then its physical size is \( \approx 46 \times 34 \) pc\(^2\), which is consistent with the typical physical sizes of SNRs with known distances for a surface brightness of \( \approx 8 \times 10^{-21} \) W m\(^{-2}\) Hz\(^{-1}\) sr\(^{-1}\) (Green 2004). PSR 1855+02 is close to the centre of G35.6−0.4, and as noted above, Phillips & Onello proposed an association of it with the remnant. Hobbs et al. (2005) derive a distance of \( \approx 8 \) kpc for PSR 1855+02, from its observed dispersion measure, which is in reasonable agreement with this distance for G35.6−0.4. For a simple Sedov–Taylor model, with a nominal explosion energy of \( 10^{44} \) J and an ambient density of 1 H atom cm\(^{-3}\), this would imply an age of about 30 thousand years for G35.6−0.4. PSR 1855+02 has a characteristic age of \( \approx 160 \) thousand years (Hobbs et al. 2004). Thus, it appears difficult to associated PSR 1855+02 with this SNR. However, given the uncertainties in both the distance to the remnant, and the simple Sedov–Taylor model, it is difficult to say anything definitive on the proposed pulsar–SNR association.

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